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DESIGN OF AN ELF/VLF SATELLITE FOR UNDER THE ICE SUBMARINE COMMUNICATIONS

by

Gary C. Thompson

September 1988

Thesis Advisor: Richard C. Olsen

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Design of an ELF/VLF Satellite for Under the Ice Submarine Communications

by

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ABSTRACT

This thesis proposes the design of a space based tethered antenna satellite system for ELF/VLF communications with submarines in the far northern latitudes, and under the polar ice. By using the dynamo effect of a moving wire in a (geo)magnetic field, the tether cable can produce tens of kilowatts of its own radiation power. The transmitted signal of lKHz-3KHz will use whistler mode propagation to couple to the earth's field lines and follow them down to the surface. The signal can penetrate 100m of seawater, and ice of unlimited thickness. A constellation of 12 satellites will provide 75% duty cycle coverage for each submarine operating area of over four million square kilometers. Issues examined are: tether electrodynamics and mechanics, debris survivability, ionospheric radio and plasma physics, plasma contactors, satellite and constellation design concepts, cost analysis, and military mission needs analysis.

TABLE OF CONTENTS

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I. INTRODUCTION

Almost one-half of America's nuclear strategic warhead arsenal is carried aboard nuclear powered ballistic missile submarines (SSBN's). These forces, as one leg of the nuclear triad, are by mission concealed beneath the surface of the ocean, deployed to all areas of the world. The strength of this strategic arm lies in its ability to hide in the depths of the world's oceans, denying an enemy total neutralization of U.S. nuclear forces in a surprise first strike, thus allowing the U.S. an assured survivable retaliatory force. The key to submarine survivability is stealth. [Ref. 1].

Contributory factors to stealth include the vastness of the world's oceans in which to operate and hide within, and the increasing opaqueness of seawater to the electromagnetic spectrum with increasing depth, affording reduced detectability. Submarine commanders must avoid detection in order to carry out their mission and be effective, but in order to utilize their powerful ballistic missiles they must maintain a critical communications link with the National Command Authorities (NCA) for positive release instructions via emergency action messages (EAMs), a process that presently increases their vulnerability to detection. Whether or not the submarine radiates in a communication process, just to passively monitor transmissions increases the vessel's operational security problems. Seawater effectively cloaks underwater electromagnetic signals, a process that occurs for both transmission and reception. To reduce the opacity, the ship must put an antenna above the water, on the water, or just below the water's surface, a proceedure that confines the submarine's operational performance and places the submarine into a realm of increased detectability by others. [Ref. 2].

At the other end of the communications links are the initiating transmitters of emergency action messages authorizing nuclear release. Although there are several methods of transmission, multiple transmitters, platforms, and frequencies, the system is essentially for peacetime use only and is not projected to survive intact after a nuclear exchange, or even limited tactical targeting by an aggressor intent on weakening our command, communication, and control networks (C cubed).

The problem that exists, is that at one end of a vital national defense command link the transmitters are vulnerable to attack from all levels of offensive escalations, and at the other end the receivers are vulnerable to detection and further prosecution while in the act of trying to receive their own command instructions. If this communications link is severed, or if the receptor is localized and attacked, then a significant portion of U.S.

strategic forces will have been lost for each ballistic submarine that is unable to respond as directed.

The following thesis proposes a spacebased, gravity gradient, long wire tethered antenna satellite that would increase operational security and strategic systems survivability. Recent advances in technology and understandings of space environment suggest new methods of communicating with submarines that would be superior to existing systems, including the ability to communicate above 70-80 degrees latitude and through the polar ice cap to submarines lurking beneath. A constellation of Extremely Low Frequency / Very Low Frequency (ELF/VLF) orbiting antennas proves to be a cost effective, relatively low risk technology, that could be put into operation expeditiously.

This thesis examines the principles of tethered space operations, of electromagnetic propagation in the upper and lower ionosphere from low earth orbit, and suggests a possible operational satellite (and constellation) design that would satisfy the identified security problems. It also recommends that an experimental satellite be deployed first, to test new ideas and collect data, before committing to an operational system.

Chapter II will trace the history and background of the present submarine communications network and its identified mission requirements for future operational security. Then it will discuss basic tether fundamentals and how a tethered antenna can meet the nation's security requirements. Chapter III will examine tether electrodynamics, Chapter IV space physics environment, and Chapter V tether mechanics. Chapters VI, VII and VIII, respectively, will look at the proposed tethered satellite concept and constellation system operations, program costs, and future studies, including an experimental satellite to gather data and prove concept feasibility.

II. HISTORY AND BACKGROUND

A. PRESENT COMMUNICATIONS CAPABILITIES

1. Electromagnetic Transmission Properties of Seawater

Due to the opacity of seawater across most of the electromagnetic spectrum, there are only two communications windows in which submarines may communicate from below the surface of the water. Outside of these two windows, all communications techniques require the exposing of an antenna above the water. Raising of such an antenna puts the crew at grave risk of discovery. Not only does the antenna provide a radar cross section, but its motion through the water creates a feather wake that is easily seen at great distances. Because of this risk to operational security, present and future critical communications networks emphasize the use of low profile antennas, preferably submerged. Although long wire antennas can be trailed on the surface, they are clearly discernible from an airplane or satellite. But, putting an antenna below the surface immediately restricts the frequencies available to communicate. Of the two usable communications frequencies, one is in the lower RF, and the other is in the visible spectrum [Ref. 3: pp. 223-239]. The blue-green visible option is a future possibility, and will be mentioned later. The lower RF window that is not opaque to seawater is used presently for submarine communications, and is divided into three adjacent bands: Low Frequency (LF) from 30khz to 300khz, Very Low Frequency (VLF) from 3khz to 30khz, and Extremely Low Frequencies (ELF) from 10hz to 3000hz [Ref. 4: p. 21].

Low frequencies (LF) use an exposed antenna that has a high degree of detectability. Signals at very low frequencies (VLF) can penetrate no more than about 30 feet of seawater. This forces the submarine to trail a lengthy antenna that must lie on the surface, or just under the surface. In either case, the trailed antenna can broach or affect surface water patterns, and increases the risk of the submarine's discovery [Ref.'s 5 and 6]. There are also restrictions on submarine speeds, maneuverability, depth, and the operation of its own acoustic counter detection equipment when its antenna is unreeled near the surface [Ref. 7: p. 33].

Extremely low frequencies (ELF), though allowing only an extremely low data rate, do penetrate seawater down to a sufficient depth where submarines can more safely operate with reduced operational security problems [Ref. 7: pp. iv, 49-51]. Sea-ice is essentially transparent to ELF, so under-ice operational communication depth is only regulated by how close the skipper wishes to get to the underside of the icepack, and the depth capacity of his vessel. In the rare event that a submarine does broadcast (vs receive only), a radiating antenna above the surface can be rapidly triangulated and geo-located, while a submerged ELF/VLF antenna (if used as a transmission antenna) is not directional, and would be hard to locate [Ref. 3: pp. 233- 239, 253].

2. Present Communications Networks

The existing (original) VLF network consists of worldwide ground station transmitters, augmented by additional LF stations. This system is reliable, redundant, widely dispersed, and is still operated continuously in several simultaneous modes. However, the susceptibility of fixed foreign ground stations to attack and jamming led to the development of mobile VLF transmitters, in 1973, in the form of EC-130 Hercules aircraft (soon to be replaced by a new 707-320B derivative Boeing airframe). These airborne VLF transmitters, called TACAMO, are more survivable than their ground based relatives because of their mobility, but they still transmit a signal which puts the submarine at risk to receive; the VLF signal has a shallow penetration depth. A follow on ELF system was developed to reduce this risk at the receiving end, allowing a greater submarine depth for reception, but now utilizing ground stations that are (again) vulnerably exposed. [Ref. 2: pp. 48-49].

The mobile VLF network reducea the vulnerabilities of the fixed base international VLF transmission systems, and the newly built ELF system was to have further improved upon the mobile VLF system by allowing the submarines to receive their EAMs at a greater depth. This ELF system is based in Michigan and Wisconsin, and hence is more secure than foreign installations [Ref. 8], but due to environmental and political interference, operational effectiveness has been compromised [Ref. 7: p. iii]. The present system is considered nonsurvivable in a nuclear war. Sabotage, malfunction, or a single nuclear strike can disable it permanently. Its purpose is now to serve as a "bellringer", i.e., if the signal is lost, the worst is assumed to have happened w.r.t. national security [Ref. 9].

B. SUBMARINE COMMUNICATION ALTERNATIVES

There are a number of high frequency radio satellite communications systems currently used by submarines. These HF, VHF, UHF, and EHF bands are primarily for basic communications traffic and secure voice/data (and NESP, the Navy EHF Satellite Communication Program). All present satellite communication systems require a submarine to raise an antenna mast.

There are alternative communication capabilities that can be developed in the near future. At present, one heavily investigated possibility is called SLCSat, for Submarine Laser Communications Satellite. Designed to operate in the blue-green spectrum, this laser satellite would downlink emergency action messages from the President to submarine operating areas. Submerged submarines would have upward viewing sensors to receive these signals through the water. This program has substantial scientific validity and technical momentum. It is also still in development, and a space qualified laser transmitter of sufficient power and reliability is still speculative. The first prototype satellite is well over ten years away, and the operational system is projected to be an expensive program, with cost effectiveness driving deployment timing. Realistic expectations for deployment are well beyond the year 2000, and its capability to transmit through sea-ice is also being questioned [Ref. 1: p. 45].

Other futuristic ideas worthy of mention include: (1), Sea bottom landline plug-ins, whereby the ocean bottom is crisscrossed with communication cables. At predetermined times subs are required to "plug in", either physically or through coupling, to pick up status reports. (2), Hydro-acoustic sono nodes. Here, sonobouy fields are deployed in sub operating areas and equipped with radio antennas, receivers, and hydrophone acoustic transmitters. The sonobouys are relays, converting the RF signal into a coded acoustic signal at some noninterfering audio frequency that can be received and decoded by a local submarine, or intermittently by a distant sub at convergence zones. (3), Towed submarine radio bouys connected by severable fiber optic wires of great length.

A final alternative expands upon an idea originally tendered by M.D. Grossi in 1972, considering an orbiting ULF/ELF antenna [Ref. 10]. This thesis expands on that idea, proposing a communications satellite that broadcasts in the ELF/VLF band. Common colloquialism has blurred the exact boundary division between ELF and VLF, but the expected broadcast window for this system would be between 1khz and 3khz, providing the penetration depth advantage of ELF and the higher data rate of VLF. High transmission power, short transmission path length, and focussed propagation paths to the submarine operating areas will increase the power arriving at the receiver. This approach is also expected to have low risk technology, rapid prototyping, competitive cost, early deployment, and affordable replacement and sacrifice.

C. STRATEGIC CONSIDERATIONS FOR SATELLITE SURVIVAL

An orbiting satellite is more survivable than a corresponding ground station that carries out similar functions. In a low level conflict, a ground station could easily be destroyed by a single saboteur, or tactical strike. A satellite is an expensive national resource, as are anti-satellite weapons. A satellite is not likely to be attacked in prenuclear hostilities. In nuclear exchanges, several of the following factors may determine the vulnerability of satellites.

Moving the battle into space crosses a threshold that is much more serious than attacking equivalent hardware on the ground. We have not yet fought in space. Once that boundary is crossed, it will be difficult to retreat. Satellites are considered national resources, and the loss of a space based national (security) resource would draw a much harsher retaliatory response than the loss of a ground station. Satellites are much harder to replace and provide advantages that ground stations cannot. An attacker would delay attacking a space based asset much longer than an earth based installation because of this possibly very dramatic retaliatory response.

There are hundreds of orbiting satellites in space that have been identified and cataloged, but an enemy will not know the mission and purpose of each and every satellite. The very number of satellites in orbit provides its own level of security: which satellites should one prosecute, and of course, did one get them all?

Finally, the agressor's own anti-satellite weapons are also national resources. He would have to expend considerable military resources, that are not rapidly renewable, to destroy a sufficient number of satellites at once.

Thus a satellite has at least four advantages that increases its survivability: the tactical / strategic threshold of permanently moving the battle to a new frontier, the response to the loss of a national resource, camouflage by numbers, and the resource threshold of the attacker who must ponder the commitment of his own scarce national resources.

D. IDENTIFICATION OF A MILITARY MISSION NEEDS REQUIREMENT

1. The Problem

The military defense industry has strict requirements and guidelines for the aquisition and procurement of hardware. Before any requests for proposals can be distributed, there must be a mission needs analysis that defines the shortcomings or problems with existing systems. It has become apparent that the present ELF communication system, and the previous systems superseded by ELF, are vulnerable at both the transmission end and the receiving end. The only two ELF transmission locations are vulnerable to attack and are limited in power and coverage areas. The present system is not capable of covering the polar areas, or of reasonable data rates.

2. The Solution

What is required is a system that is less vulnerable to being put out of action, provides greater power to the receiver, and covers more of the submarine operating areas, including below the polar ice cap. It should increase submarine operational flexibility. It should be redundant and inexpensive enough to be sacrificed and replaced.

Solutions for this mission need involve satellite transmitters which can offer greater survivability. Such a system would increase the operational effectiveness of our stategic nuclear forces by ensuring that emergency action messages get transmitted with a higher degree of reliability and survivability in a nuclear exchange or crisis.

E. TETHERS

1. Tether Fundamentals

Tethering, as a concept, was first described by Tsioklovskii in 1895 as a possible space tower to weightlessness. If an equatorial tower were built to extend beyond geostationary altitude, one would experience weightlessness at geo, and "inverted gravity" farther out, i.e., centrifugal force. In 1960 a Russian engineer, Artsutanov, suggested that a massive satellite be "anchored" in space and a cable be dropped down until it touched the earth. In the opposite ("upward") direction from the satellite, a cable would be deployed with a ballast mass to offset the earth deployed cable mass, such that the satellite maintains a center of gravity that remains in geosynchronus orbit. In the 1970's the idea gained a more practical aspect as more concepts were developed, particularly in using the space shuttle orbiter as a research tether platform, as in Colombo's (1974) concept of tethering a subsatellite 100km below (or above) the shuttle to conduct atmospheric and magnetospheric experiments. [Ref. 11].

Basic tether fundamentals can be best described by quoting from the introduction of "Tethered Satellite System (TSS) Core Science Equipment", by C. Bonifazi [Ref. 12], and by referencing Figure 2.1 in the Appendix at the end of the thesis:

> ...The principle by which the system works is quite simple and can be explained with reference to Figure 2.1 showing the stabilizing forces acting on tethered masses. An elementary tether system has "dumbbell" form with two masses connected by the tether. The top mass experiences a larger centrifugal than gravitational force, being higher than the orbit of the center of gravity, whereas the reverse occurs at the bottom mass. Displacing the system from the local vertical generates restoring forces at each mass, tending to return the system to local vertical. The system will remain aligned with the local vertical or "gravity gradient" vector. The center of mass, halfway between equal masses, is in free fall, but the end masses are not. The top mass travels too fast for its altitude, thus giving rise to the excess centrifugal acceleration felt as tension in the tether, with the inverse occurring in the lower mass. The masses experience this tension as artificial gravity....

In this proposal the tether is an antenna tensioned by artificial gravity, and stabilized along its entire length with the local vertical. If the vertical tether is also a conductor, and it is in a low equatorial orbit cutting the earth's magnetic field lines almost perpendicularly, then we have in effect a generator (a moving dynamo), and a generated electromotive force along the wire. In the moving reference frame of the wire there is an electric field perpendicular to both the orbital velocity vector and the geomagnetic field vector, and this field vector is directed along the wire. The generated electric field results in an emf in the wire, making one end of the tether positive and the other end negative. Electrons collected at the positive end will be pumped to the opposite end via this emf boost, producing a tether current. Plasma contactors at each end can be designed to more efficiently exchange electrons with the surrounding plasma than the bare wire ends can, thus increasing the level of current. If a load is inserted in the wire, then the flowing current can be harnessed for work. Work comes at a cost however, because the power extracted across the voltage drop comes out of the angular momentum of the system. Removing work from the system causes electromagnetic drag which decelerates the system and drops it into a lower orbit. This decay will continue until atmospheric drag becomes the predominant drag force, and rapidly destroys the system.

The concept can also be reversed. If a current is pumped through the wire in the opposite direction from its normally self generated direction (from a separate power source), then the system is accelerated within the geomagnetic field and boosted to a higher orbit. Thus, extracting power out of the tether drags the system to lower orbits, and pumping in power boosts the system to higher orbits. If that load should be a transmission antenna, then by alternating between normal drag modes and powered boost modes, at ELF cycles, one can obtain an ELF radiating antenna in orbit that is gravity gradient stabilized and altitude controllable. The next two chapters will examine tether properties and the space environment more closely.

2. Tether Programs

The history of tether programs, and related antenna studies, goes back a short time, with only a few directly related experiments. In late 1966, the Gemini XI and XII spacecraft and the Atlas-Agena D exhausted stage were coupled in the first tethered application experiments. Two modes of operation were examined. One mode explored inducing angular momentum into the tethered system via translational thrusting, and the other mode studied the stationary gravity gradient motion of the system. Both experiments were successful and verified analytical assumptions. [Ref. 11].

In 1971, the OV1-21 satellite experiments (NASC-117) showed that straight-forward transmitters were not effective at driving electrical dipole tether antennas at ELF/VLF frequencies (400hz - 14.5khz) because antenna impedances varied wildly. This problem was a result of the coupling between the antenna and the surrounding conducting plasma environment [Ref. 13]. A solution to this problem would be to better connect the ends of the tether antenna to the immediate environment through the use of plasma contactors, or better yet, to use the naturally occurring tether currents, modulated at the appropriate frequency (ELF), to drive the antenna.

The United States and Japan conducted a series of tethered rocket experiments in the early 1980's. A significant experiment called Charge 2 [Ref.'s 14 and 15] studied the effects of a 200 meter tether wire as an antenna in the VLF bands with electron beam emissions, and then again when the tethered system's bodies (mother and daughter satellites) were charged to high voltages.

In November, 1985, MAIMIK was launched to study electron beam interaction with a plasma environment and neutralization of charged vehicles in the ionospheric plasma. Also examined was how the non-neutralized plasma wake behind a space vehicle is modified by electron beam emissions. [Ref.'s 16 and 17].

There is one major funded program in the near future, called Tethered Satellite System One (TSS-1), to be launched around 1991 as a shuttle orbiter payload. It is a joint Italian-American project that will examine tether dynamics and electrodynamics. With the shuttle at a 200km orbit, one test will deploy a subsatellite upward on a 30km tether to examine interactions with the earth's magnetic field, energy generation, and thrust production. Mesospheric studies of this kind are virtually impossible by other techniques. A proposed (but unfunded) mission will lower a subsatellite down a 100km tether to study the upper atmosphere. [Ref. 12].

3. Tether's Future

While tethers are a relatively new concept (historical experiments are few, and present applications limited), the science and space related journals are publishing many new ideas on how to use them. This thesis proposes a very basic use of the tether, as an antenna, but there are some very novel and ingenious proposals suggesting new uses. Some of these are: a power generation system using the dynamo technique; space station applications such as microgravity experiments; gravity gradient fuel (or liquids) transfer in space; micro-g materials processing; conservation of angular momentum when deorbiting spacecraft or garbage; and the transfer of angular momentum between bodies for various purposes, including Mars space operations [Ref. 18].

F. THE SPACEBASED ELF/VLF TRANSMITTER AND MISSION REQUIREMENTS

This thesis is proposing that an ELF/VLF, spacebased transmitting antenna system, be placed in orbit. Using well identified basic concepts, this satellite system will be composed of a constellation of gravity gradient stabilized antennas, each antenna several kilometers in length and in complementary orbits, but with propagation paths that permit communications with submerged submarines in those operating areas which are poorly covered at present, particularly under and near the polar ice cap. By moving the critical transmitters to space we increase the likelihood that the message will get out because of increased transmitter survivability, reliability, multiple satellite redundancy, power reception density increases, and coverage patterns.

Using a gravity gradient approach for antenna construction provides a stable platform with a constant and known orientation. By driving the antenna alternately between its natural current state and the powered state (with the use of plasma contactors) we obtain an effectively radiating antenna system. As will be shown in Chapter IV, by using the properties of the earth's geomagnetic field, and plasma physics in the ionosphere, we can "focus" our propagation paths directly to the areas of desired coverage (increasing the received signal strength and the penetration depth of the signal), thus further increasing operational security by limiting and controlling areas of reception / interception. In the next chapter the physics of tether electrodynamics will be studied and Chapter IV will examine the near-earth space environment.

III. TETHER ELECTRODYNAMICS

A. MOTION INDUCED ELECTROMOTIVE FORCE

A conductive wire in orbit with an earth radial orientation, that cuts the earth's magnetic lines of force, will develop a voltage potential across its ends. If "v" is the tether velocity vector, "B" the geomagnetic field strength vector, "l" the tether direction vector, "L" the tether length, "I" the tether current, "X" a cross product, and "." the dot product, then the electric field is (v x B), the associated voltage is (v X B . l)*L, and the Lorentz force is (I X B).

Opposite ends of an insulated conducting tether will accumulate opposite charges based on the induced emf. Current will attempt to flow through the tether, and the end "electrodes", drawing from the available electron plasma. The ionospheric plasma is itself a conductor, so electrostatic fields between the ends, and external to the cable, will slightly reduce the accumulated charge that the moving conductor emf boost created. The plasma sheaths at each end of the tether act as either charge reservoirs or sinks, depending on the orbital direction of motion. The ionospheric plasma allows for the return current path to be completed, supporting a continuous current flow through the wire, and into the plasma. [Ref. 19: p. 3].

If we assume v is to be east (the tether orbital velocity and direction), and B north, then (v X B) is up. If the end electrodes are inefficient in exchanging charge with the surrounding plasma, there will be minimal current flow induced in the insulated tether wire, and the ends will develop large voltage potentials with respect to the local plasma, with positive at the top and negative at the bottom. If the electrodes (commonly called plasma contactors) can be made more efficient in their current coupling so that significant current can be passed through the tether and into the plasma (with an insignificant voltage drop across the connection junction) then the tether ends will float at the local plasma potentials. The entire open circuit voltage (v X B . L) will be across the tether and any loads in series with the tether.

Due to the properties of insulators, they have much higher breakdown voltages if they are surrounded by positively charged plasmas than by negatively charged plasmas. Therefore, a load should be placed at the negative end of the tether (the bottom), because that would leave the majority of the tether length negative with respect to the surrounding plasma. In the same vein, if the tether is to be used as a thruster, by reversing the current flow and overcoming the emf, then the electrical power source should also be inserted at the bottom (negative) end. Figures 3.1 and 3.2 diagram the tether potentials in both the generator and thruster modes. In both figures, the tether is deployed upwards, and the load or power supply is at the bottom. Typical voltages that might be induced by a 20km long tether range from 1500 to 4500 volts, depending on the angle at which the field lines are crossed. [Ref. 20].

B. MAKING CONTACT WITH THE PLASMA

A plasma contactor needs to fulfill several performance criteria. In order to make the system efficient, and the return path impedance low, the plasma contactor should have a low resistance to current flow. It should have minimal power consumption, and it should be capable of electron (or ion) emission as well as collection (for switching between the generator and thruster modes). A general implementation of a contactor can be visualized as a balloon. The contact surface area is great, and the method is mass and energy efficient, so it is an effective electron collector. Unfortunately, as a positive charge collector, the current limits are restricted to microampere levels. To improve upon simple collection of positive charge one could emit electrons through thermionic emission and electron guns. Higher positive current is definitely available with this option, but plasma impedance and filament energy losses are significant [Ref. 21]. The most effective method to date uses a device called a Hollow Cathode to produce an expanding cloud of highly conductive plasma. The plasma cloud is then the (enhanced) collecting surface (Figure 3.3, Ref. 22). The cloud expands until the electron thermal current flow balances the random ambient ionospheric electron density. Hollow cathodes can be operated in either current sense: they can be placed on either end of the tether, and driven in both directions [Ref. 23]. Figure 3.4 [Ref. 22] is a schematic diagram of an electrodynamic tether system interacting with the ionospheric plasma.

A hollow cathode (Figure 3.5, Ref. 22) consists of a narrow tube with a gas expellant orifice plate on one end and a cathode insert with heater at the other end. A disk (or toroidal) anode is positioned just off of the end of the tube near the cathode. To make the hollow cathode operate, gas is ejected out of the orifice, building up slight pressure in the hollow cathode. The heater is energized and the anode is biased by several hundred volts positive. Figure 3.6 [Ref. 22] is a cross section of a hollow cathode in operation. The thermionic electron emission flows have ionizing collisions producing electron / ion pairs. Ions bombarding the insert heat it further. This heating causes cathode discharge ignition which is self sustaining and allows the heater to be eventually turned off. The anode accelerates, separates, and collects the respective charges from the hollow cathode plasma discharge. It is the charged pair production process that forms the plasma downstream of the hollow cathode. [Ref. 22].

An electrode placed downstream of the hollow cathode assembly can collect electrons or ions from the hollow cathode plasma plume, depending on whether the bias is positive or negative. Thus the plasma contactor can be used as either an electron or ion emitter. If the downstream electrode is a plasma, instead, then the electrons in the plasma will be collected by the hollow cathode when it is biased to emit ions. If the cathode were biased to to emit electrons, then ions would be collected from the space plasma. Thus, by changing the polarity on the assembly, either electrons or ions can be emitted to form the plasma cloud collector, drawing in charges. Charges intercepted by the cloud are directed via coulomb forces towards the anode at the end of the tether, to form the tether current. The Ring-Cusp Ion Source and the Closed-Drift Ion Source are two newer devices that are hollow cathode derivatives with higher efficiencies, but higher complexity. [Ref. 22].

Some studies indicate that as total current is increased, at fixed potentials, the plasma cloud contracts, increasing the emitter voltage drop and increasing return path impedance [Ref. 24]. This implies that power production efficiencies, and current gain, drop at higher tether current levels. Current gain is the ratio of the total current (the tether current that flows through the contactor system into the plasma, e.g., electron collection) to the emitted ion current (which determines the energy and mass expended). The only other expenditures are for initial cathode heating and a constant, but very slow, emission of gas for a plasma. It is suggested then that high tether current demands would be more effectively met with multiple plasma contactors (on separate cables) than one large plasma contactor.

C. DRAG AND DECAY

When the tether is generating electrical power, an electrodynamic force is also generated that opposes the direction of motion. This drag force is opposite the tether velocity vector and is of magnitude Force $F = (I \times B)*L$. The electrodynamic power involved is $P = (F \cdot v)$ [Ref. 19: p. 3]. The associated decay time to fall out of orbit is $(da/dt) = (3.6*24)(2F/mw)$ in km/day, where "F" is the electrodynamic drag force, "m" is the mass of the tethered satellite system in kg, "w" is the orbital motion in rad/sec, and "a" is the orbital height in km. If L = 50km, m = 1800kg, and a and w are for an altitude of 1000km, then the naturally powered tether operating 100% of the time will decay out of orbit in under two days [Ref. 10: p. 3]. Obviously there must be compensating reboost to keep the system operational for any length of time. Atmospheric drag becomes significant when below altitudes of 250km. The more active the system (drag and boost), the less important short term aero-drag will be, except for aero-drag forces so severe that assymetrical loading occurs on the lower mass.

D. RESISTANCE AND IMPEDANCE LOSSES

An equivalent circuit for a tether current model includes three resistors in series with a battery ("Vbat"). The resistances include the tether cable resistance ("Rt", typically the largest loss in the system at 5-30 ohms per km), ionospheric resistance ("Rion", the return path and included effective plasma contactor resistance, typically 2-50-100 ohms total), and the load impedance ("Zl", which is the work load or energy storage load). The total voltage drop across the entire system is the sum of the individual voltage drops and is equal to (v X B . l)*L, or Vbat = vBL in equatorial orbits. "Vbat" is the induced voltage. Current flow ("I") depends primarily on the load impedance Zl, where I = (Vbat)/(Rt+Rion+Zl). Power available for the load is the standard (I**2)*Zl. Let "Vrev" be the reverse power supply voltage necessary to drive the same current level in the reverse direction (i.e., as in thruster operations, or reboost). Then Vrev = (2*Vbat - I*Zl). Note that the reverse voltage must be twice the self generated voltage to produce the same current level in the opposite direction. That means for balanced antenna radiation, internal power expenditure will be twice the self generated power expenditure during the broadcast period. [Ref. 10: pp. 5-8].

The return current path through the plasma is a complex and poorly understood process. Although electrons are bound to follow the field lines, if there are plasma density discontinuities or turbulence, electron motion may be disrupted, causing electrons to join a new field line. This results in a random walk that completes a current loop between the two plasma cloud plumes. This return path also has highly variable, and nonlinear, impedance properties that are dependent upon current densities and oscillation frequencies (among many other unidentified processes) [Ref. 13]. For practical purposes, most present discussions assume infinite charge sinks at both ends, and ignore ionosphere drops. With proper plasma contactors, the return path impedance can be brought fairly low. Additionally, after tether deployment, any tether cable still left on the deployer drum will have a residual impedance effect (inductance) on the system, and induce greater losses than if it were completely deployed.

The largest loss of power is due to the resistance of the tether cable. The percentage of tether cable resistance to total system resistance is also the percentage of power that is wasted as heat in the tether conductor. Tether temperature depends on solar conditions, materials, current, and orientation. There is a finite limit on the steady state current carrying capacity of the tether, and this current limit is determined by the tether's maximum allowable temperature and its heat dissipation characteristics. Any increases in thermal energy input must be balanced by radiation outward against any influx radiation (i.e., solar at 1400 watts/sq.m, and reflected solar). Any power saved through reduction in unit tether resistance is made available for the load. Primary in-orbit control of load power comes by controlling the load resistance. By reducing load resistance, more current can flow, providing more power (or radiated power if the load is an antenna). Any solution must use the lowest possible resistance per unit length that weight will allow. Larger diameter cables conduct current better, and can bear more tension, but their cost is in increased weight.

E. ALTERNATING POWER AND MODULATION

The normal mode of operation, the natural self-generator mode (self-powered), produces electrical power at the expense of orbital energy. For an eastward orbital direction, the natural tether current will be up (electrons down). The thruster mode of operation increases orbital energy by pumping current in the reverse direction. Internally powered current will flow down, i.e., electrons up. If these alternate modes of operation are cycled at ELF frequencies, with the generator and thruster current levels the same, but in opposite directions, then the tether can be used as an ELF antenna and the system will remain at a constant altitude. In one frequency cycle there are two phases, and each power source will furnish power for one of those phases. The internal power supply needed for thrust and transmission power can be solar cells, batteries recharged by solar cells, or other methods such as nuclear, isotope, and chemical.

When the tethered antenna functions in the "on" duty cycle mode, it is performing alternately as a natural self generator, supplying power for radiation in every other half phase of the frequency cycle, and then as a thruster. The power for the opposite half phase during this mode comes from onboard energy sources (solar and / or battery). If solar power is insufficient, battery drain will occur. If solar power and battery are both inadequate to match the self generated power during radiation, then orbital energy will decrease, manifesting itself as orbit decay. Energy can be reinjected into the orbit with powered electrical reboost, after the broadcast, from onboard power systems [Ref. 10: p. 10]. The broadcast period will be no longer than ten minutes.

When the ELF transmitter is in the "off" duty cycle mode, continuous DC power supplied from the available solar (or other non-battery onboard power systems) can be used to reboost the tethered satellite system, if necessary, and recharge the batteries. If reboost is not necessary, then solar power can be dedicated to battery rejuvenation. The system may need to be designed to perform in this boost / drag operational manner, depending on the required duty cycle, to save mass in the power supply system. To accept this alternative means accepting variable perigees and apogees that can be recorrected by reboost, or even altered further for orbit flexibility. There would be no effect on the orbital plane inclination other than the effect of the equatorial bulge rotating the line of nodes. The system will remain in the off cycle for 90% of its orbital period.

This ELF oscillating signal can be modulated to carry information. Standard methods using amplitude, frequency, or phase modulation do not work well on a signal of such low frequency. A better technique is to use pulse position modulation (PPM). In this method, one side of the waveform's rise time (either the natural or powered pulse) is advanced or delayed in time, while the other phase of the wave maintains a constant time interval, being the sync [Ref. 10: p.12]. By digitally encoding the data, such that the PPM signal has only two states, error codes can be included in bit windows, increasing data rates for greater flexibility and reliability.

F. ALTITUDE AND INCLINATION EFFECTS

All the considerations so far have been for low earth orbits (LEO) in the equatorial plane (inclination "i" of 0). In a pure polar orbit (inclination of 90), the vertical wire tether runs mostly parallel to the field lines, so there is no induced emf voltage. There would be some voltage, however, because the magnetic poles are displaced roughly 11 degrees away from the geographic poles. The magnitude of the equatorial induced emf is a cosine function of inclination. Thus, in a polar orbit the minimum voltage would be 0 if the satellite track passed over the magnetic poles. In an equatorial orbit voltage variations will swing from the full vBL, to the cosine of (0,+-11 degrees) times vBL, or .98 of vBL. An orbit with i = 60 degrees will result in 50% less generated emf capability, and a corresponding reduction in current flow. A 50% reduction in current is a 75% loss in available power. A 50% power loss would be experienced at an inclination of 45 degrees. At 66.7 degrees the power loss is 84%. At 80 degrees of inclination, the maximum self generated equatorial power is .03*vBL.

The case of tether self generated power when the system is not crossing the equator will be examined in the next chapter. The special case of the satellite at its maximum latitude will be used. This is the orbital segment when self generated power will be utilized to provide radiation transmission power for downlink communications.

Changes in the tether altitude results in two effects. First there is the decrease in the geomagnetic field strength as the inverse cube of the increased orbit radius. The second cause is smaller, and is due to the reduced velocity of the tether relative to the earth's surface (and geomagnetic field) at increased orbital altitudes. The combined effect is an induced voltage that varies as the inverse 3.5 power of the orbit radius. With voltage proportional to current, and power proportional to current squared, the power available is proportional to the inverse 7 power of the orbit radius. If we take the power available at 500km as 100%, the power available at 1000km would be 61% (one earth radius is 6370km). [Ref. 25: p. 2].

IV. THE IONOSPHERE AND BEAM PROPAGATION

A. THE IONOSPHERE

The ionosphere is an atmosphere of ionized gases and electric charges that is broken up into descriptive regions starting at 50km and extending to above 600km. These regions, or layers, are called the D, E, F layers, and extend to the 'topside' ionosphere. The D layer ranges from 50 to 85km, the E layer from 85 to 140km, and the F layer extends to 600km (F2 approx. 200-400km). The topside ionosphere merges eventually with the magnetosphere, above 1000km. Electron density w.r.t. altitude reaches a peak in the F2 layer, at roughly 10E6 electrons per cubic centimeter. Figure 4.1 illustrates the electron concentration as a function of altitude for the mid latitudes. Electron concentration varies between day and night, with the seasons, and solar activity. In the altitude range of 300 to 700km, electron concentration does not vary significantly with altitude in the northern latitudes near Iceland. This is the region which will be mentioned frequently in the forthcoming development of a communications case model centered on this geographic area. The altitude of 500km will be used as a good average altitude for the satellite antenna.

The presence of electric charges in the upper atmosphere affects the transmission of radio waves (via wave-particle interactions), by attenuating the signal or reflecting it. When radio frequency (RF) energy encounters free electrons, some of the energy of the wave is transferred to the electrons in the form of oscillations at the RF frequency. These oscillating electrons then reradiate the same RF wave, restoring the RF signal. If, however, the neutral gas density is high, the oscillating electrons will collide with the neutral particles. Energy is lost to the neutral atoms in the form of thermal energy, reducing the available electron energy that can be reradiated at the original RF frequency. This attenuation in signal strength is precisely what happens at the D layer because of the high density of neutral atmospheric molecules. The lower the frequency, the greater is the attenuation factor. Attenuation due to neutral collisions decreases with increasing altitude, and is relatively small in the E and F layers.

As one approaches the F2 layer from either above or below, the electron density increases, increasing the phase velocity of the electromagnetic wave (for a constant frequency), and decreasing the effective index of refraction. Thus, the larger the electron concentration, the smaller the refractive index for that ionospheric medium. For specific frequencies, certain electron densities produce zero indices of refraction. A wave transiting high indices and reaching a zero index will be reflected. Higher frequencies will reflect at higher electron densities. Since maximum electron concentration is at the F2 layer, there is a maximum frequency that can be reflected, above which RF signals will pass through without reflection. At angles of incidence other than normal, the effect is more refractive than reflective. The electron density required to reflect the the angled wave front is then less. Decreasing the angle of incidence increases the maximum (critical) frequency that can be reflected along that path. All frequencies below the critical frequency will be reflected. The lower the frequency, the lower the altitude that will reflect the signal. The smaller the angle of incidence, the lower the altitude at which it will be refracted. This is how long range communications systems work, by bouncing signals off density layers in the ionosphere.

In general, under normal operating circumstances (i.e., regular communications systems) an RF signal of low frequency (such as ELF or VLF) will be strongly affected by both attenuation in the D layer, and by reflection or refraction. There is, however, another propagation mechanism which is effective at ELF, and that is the whistler mode.

An audio amplifier system hooked up to an elevated long wire antenna will receive RF atmospheric noises in the audio frequency range. Often these noises will resemble a falling pitch tone, or whistle, hence the name whistlers. It is known that whistlers emanate from lightning flashes near the earth's surface. The low frequency electromagnetic energy penetrates the upper ionosphere and then couples to a magnetic field line, following it to the opposite hemisphere, to a magnetic conjugate point. The "whistler" behavior is due to the way in which the index of refraction varies with frequency. Lower frequencies have a lower velocity, thus a delayed arrival time. The transport mechanism is believed to be a natural waveguide resulting from the particular characteristics of electromagnetic VLF wave propagation in a magnetoplasma. These natural waveguides in the magnetosphere act as tubes, guiding the signal along the geomagnetic field lines. Whistler wave front normals within 20 degrees of a field line will be coupled and transported. Several different paths are believed to exist that transport the signal, ranging from subprotonic whistler paths that bounce between 100 and 1000km, to ion cyclotron whistlers that may extend out to several earth radii. [Ref. 26].

The attenuation rate for a whistler waveguide path is shown in Figure 4.2 [Ref. 27: p. 10-38]. Figure 4.2 plots the calculated ELF ionosopheric penetration losses through the earth's ambient day and night ionospheres, through to the earth's surface. The graph is representative of the losses that would occur at high geomagnetic latitudes and is for plane waves incident on the ionosphere in a direction parallel to the geomagnetic field. These losses are not per path length traveled, but per trip through the ionosphere.

Figure 4.3 [Ref. 27: p. 10-27] shows the attenuation rates for propagation in the Earth - Ionosphere waveguide. They show the daytime and nighttime attenuation rates in decibles per million meters of path length for frequencies between 5 and 2000 hertz. These two graphs are for the earth ionosphere-waveguide trap; for signals following the earth's curvature, bouncing between the ground and the lower ionosphere. For 2000 hertz (daytime) the attenuation is 30db / megameter. A nighttime 2000hz signal is extrapolated out to 15db / Mm. Daytime attenuation losses are twice the nighttime attenuation losses.

Note that both Figures 4.2 and 4.3 are sensitive to the time of day, and both show increased attenuation at higher frequencies. It can also be seen that smaller losses occur in penetrating the ionosphere from space than from bouncing the signal in the earth-ionosphere waveguide. The losses from space penetration also occur only once. Losses in the ground waveguide are dependent upon distance. A frequency of 1khz-3khz would be attenuated by 10-15db in the daytime, but much less than 5db at night in penetrating the ionosphere. This frequency range also appears to be the upper effective ELF communication frequency that can easily penetrate the ionosphere, using whistler propagation along field lines (during the the daylight hours). The net penetration attenuation for an ELF signal from a satellite should then be no greater than 15db, and an additional 30db / Mm for the ground hop portion. [Ref. 27].

B. THE GEOMAGNETIC FIELD

The earth's magnetic field can be modeled after a simple dipole magnet located in the center of the earth, but tilted away from the rotational axis by approximately 11.5 degrees. The geomagnetic north pole is located at 78.8 degrees North, and 70.9 degrees West, relative to the geographic coordinate system. Future references will round these values to 79N and 71W (289E). The dipole model is 10 percent accurate out to several earth radii. Adjustments to the dipole model can bring it to within 2.5 percent accuracy. Specific equations for field strengths at various altitudes and zenith angles can be computed from formulas listed in the appropriate bibliographic listings. The field strength over the earth, at an altitude of 500km, is depicted in Figure 4.4 [Ref. 28]. In this chart, lines of constant magnetic field strength are ploted on a map of the earth's surface, with lines of latitude and longitude marked appropriately. The strength of the geomagnetic field is important if the tethered satellite is to be evaluated as an electrodynamic generator or propulsive unit.

Geographic latitude can be converted to geomagnetic latitude either by referencing maps printed in geomagnetic coordinates, or by calculating those magnetic coordinates directly from formulas. Figure 4.5 [Ref. 29] is a geomagnetic map of the world, circa. 1960. If the Greenland - Iceland - United Kingdom expanse (here after called the GIUK gap) is examined, one would note that Iceland is roughly centered in the middle of this waterway. This happens to be a submarine transit area, and will be the area of examination in this communications model. The geographic location of Iceland is roughly 65 degrees north, and 340 degrees east (20 degrees west). The entire gap ranges from 60 to 70 degrees north geographic. Ice pack operations would be possible starting around 75+ degrees north geographic. The chart shows that the corresponding geomagnetic latitude for Iceland is 70 degrees north magnetic. Note that with a magnetic latitude of 70 degrees north, Iceland's magnetic latitude differs by 5 degrees from its geographic position. The previously quoted geographic range of 60 to 70 degrees north is shifted by 5 degrees to become 65 to 75 degrees north magnetic.

Once the magnetic latitude is known, the magnetic dip angle can also be calculated. The magnetic dip angle is the angle that the local geomagnetic field line makes with the earth's surface. The magnetic dip at the magnetic poles is 90 degrees, and at the geomagnetic equator it is zero degrees. In between, an approximate value can be calculated using the dipole approximation applied to the earth's surface. Using Iceland at a magnetic latitude (ML) of 70 degrees north, then with substitutions, and ignoring local inconsistencies, the solution equation is:

$$\text{ArcTan } [2(\sin 70)/(\cos 70)] = 80 \text{ degrees.}$$

Again, the range of 65 to 75 degrees north magnetic produces dip angle ranges of 77 to 82 degrees from the horizontal. This dip angle is the angle for whistler mode propagation arriving in the GIUK gap vicinity. The southern edge of ice pack operations would have a dip angle of 85 degrees. On the other side of the northern hemisphere, at the Bering Sea and northward, the geomagnetic sphere is rotated northerly of the geographic sphere. Hence, magnetic latitudes are several degrees south of their corresponding geographic latitudes, and dip angles are also several degrees less than at the same geographic latitude near Iceland.

C. THE WAVE PROPAGATION MODEL

The purpose of the proposed communications system is to communicate with submarines in their operating areas. These areas will be in the northern latitude waters and under the ice. In order to establish the validitity of the concept of using whistler mode propagation techniques as the communications method, a geometric and mathematical model will be constructed, and this model will simulate a communications link to the GIUK gap. This area has been selected because: (1) The GIUK gap is where US and foreign subs both patrol and transit, (2) The northern ice pack is relatively nearby, (3) Except for the Hudson Bay - Greenland transit area, the GIUK is the northern-most operations area w.r.t. the geomagnetic sphere, located in a higher magnetic latitude magnetic dip angle. As will be explained later, lower magnetic latitudes (with lower dip angles) increases the power available for the receiver on the ground. The GIUK is the most difficult scenario in which to establish a whistler communications link.

In constructing a model, several methodological techniques should be applied for a model to be easily accepted. Five concepts were applied to this model:

1. Generalizations - keep things simple and use approximate values where ever possible. Simple models have longer lifetimes, are more flexible, easier to change, and are comprehendible.

2. Reasonableness - use concepts and steps that are intuitively obvious, that are reasonable and acceptable.

3. Conservatism - use proven and logical steps that are widely approved of.

4. Pessimism - lean toward conditions that would hinder success or completion. By stressing the model and proving capabilities in worst case situations, then success is ensured in normal expectations.

5. Reproducibility - if the reader can immediately duplicate the model in his mind, and it seems logical, then it is probably true and applicable.

The model that follows will be reasonable, simple, and leaning towards a worst case situation, hoping that any conclusions drawn here would be conservative answers when compared to reality. Examined will be the antenna radiated power that is coupled to the field lines, the signal path loss, the radiated power density on the earth's surface, received signal level, main beam footprint, side lobes, and coverage area. Much technical research is being done in ray tracing, and still needs to be done, but this model will demonstrate minimum expected capabilities and proof of concept.

The following are the initial assumptions:

1. The tethered antenna has a length between 1 and 20km.

2. The coupling angle between the field line and the wave front normal is less than or equal to 20 degrees.

3. The magnetic dip angle at Iceland is 80 degrees.

4. The ground dip angle of 80 degrees is extended into space, so that a satellite will also see the same dip angle on its antenna.

5. The magnetic pole, the satellite antenna, and the receiver will all be in the same plane defined by a common magnetic meridian.

6. The wavelength will be between 100 and 300km, for a frequency between 1000 and 3000hz.

7. The satellite will be in an orbit between 200 and 1000km (average of 500km), because it must remain in an environment of high electron density in order to utilize self powered properties.

8. The efficiency of the antenna as a radiator will not be considered. Only the actual radiated power will be considered, not how much power is required to pump the antenna to produce the radiated energy.

9. Within the coupling angle of 20 degrees, 100 percent coupling is assumed. This is reasonable because although the nearest field line within 20 degrees may not couple all of the available energy, the next field line will absorb a percentage of the remainder, and so forth at greater distances until essentially all of the available energy has been coupled.

10. The whistler propagation mode is a reversible process, with the 20 degree coupling cone operating along the entire field line and at both ends. A signal can couple and uncouple at either end, within 20 degrees of the field line.

11. Any radiation produced by non-symetrical return currents through the ionospheric plasma will be neglected.

12. The orbit will have an inclination of 65 degrees to bring the satellite over the Icelandic operation area. An equatorial orbit cannot be used because at this low altitude the field lines the antenna would couple to (in the whistler propagation model) would intercept the Earth well south of Iceland. Going higher than 1000km reduces the electron density, which is necessary for powering the tether as a generator.

1. The Coupling Model

First, the power available to be captured by the field line must be determined. It is not entirely clear if a 10-20km antenna in the topside of the ionosphere can be addressed as a dipole antenna. There is much work being done to evaluate these radiation patterns, hence a limiting case will be considered. A long wave dipole antenna typically has a radiation pattern similar to a donut, with maximum transmission efficiency in a direction perpendicular to the antenna axis (around the equator), and minimum efficiency of the ends of the axis. Figure 4.6 illustrates the radiation gain pattern for a typical dipole antenna. The gain of a perfect dipole is 1.64 when the antenna's axis is parallel to the RF wave front. The gain of the antenna along its axis (off the ends) is zero. Thus, the amount of power the antenna can transmit to a specific point in space depends on how many degrees away from the antenna's equatorial plane the point lies. A dipole shorter than the optimum length will have reduced gain.

To approximate the power density (watts per square meter) that a point in space would receive from a dipole antenna, one must first determine how much power that point would receive if it were the same distance away from a point source antenna radiator, with a spherical (isotropically expanding) wave front. Multiply the energy density at that distance times 1.5 for the approximate maximum gain of an inefficient dipole antenna along its equator. This product represents the maximum power density that can ever be received at this distance, irrespective of antenna orientation. To take into account antenna orientation w.r.t. the same selected point, square the cosine of the included angle formed by a line joining the center of the antenna and the point, and the antenna's bisecting plane (the plane of its equator). Multiply this value by the previous product. An example follows.

When the antenna transmits, all wave front normals within 20 degrees of the intersecting magnetic field lines will couple, according to whistler mode physics. The case of a field line laying in the antenna's maximum gain plane (therefore also perpendicular to the antenna's axis) is first considered, and Figure 4.7 illustrates the situation. Since the coupling angle for the field lines is 20 degrees, only the energy inside of a cone emanating from the center of the antenna that has a half angle width of 20 degrees (which is a total of 40 degrees) will properly couple to the field. The area that the base of the cone inscribes on the surface of the isotropic sphere, divided by the total surface area of that sphere, and times a gain of 1.5, is the maximum radiated power that can be coupled to the field, based on a one watt transmitter. The ratio is roughly 4.5%, or 13.5db below the total transmitted power "Pt". This is the maximum power that can be transferred into the communications link in this worst case evaluation. "Pa" is the maximum power available to couple to the field lines.

$$Pa = .045 * Pt$$

$$Pa = Pt - 13.5db$$

The probable power that can be transferred into the field lines is closely related to the dip angle, and its relationship to the gain pattern of the antenna: a long wave, dipole antenna pointing directly at the earth. If the dip angle were 0 degrees, so that the field lines were perpendicular to the antenna's axis (and aligned with the antenna's wave front normals), then the maximum available signal energy of .045*Pt would be coupled. This would be the case at the magnetic equator. In the geographic area of interest, the dip angle is closer to 80 degrees, near the end of the antenna where it is less efficient in its transmission abilities. If the dip angle were 90 degrees, there would be no available energy to couple to the field lines. Along the antenna's axis, the effect of the dip angle on power density can be estimated with a cosine squared function. Therefore at 80 degrees of dip, the cosine squared of 80 degrees is close to .03, or 3% of the maximum available power to couple, an additional 15db of power lost. "Pc" is the coupled power (for an 80 degree dip angle in this case).

$$Pc = .03 * Pa$$

$$Pc = Pa - 15db$$

The total net signal power that can be coupled to the field lines over Iceland is now .00135*Pt. The net power summary is:

$$Pc = .00135 * Pt$$

$$Pc = Pt - 28.5db$$

Figure 4.8 shows the dip angle relationships and a crosscut slice of the area of illumination below the antenna. The view is looking east. North is to the left. The northern edge of the cone of illumination makes a 30 degree angle from the antenna axis [(90 - 80) + 20], and a 60 degree angle with the lower ionosphere and the earth's surface (flat earth). Figure 4.9 views the top of the antenna, looking down on the earth from above. It shows the pattern as it spreads in a northerly direction. If it were not to eventually intercept the ground, the energy inside the 40 degree cone would continue outward, gradually decreasing in intensity as the field lines absorbed the energy. Figure 4.10 views the antenna along the magnetic meridian, looking south. Here the ideal dipole pattern can be seen and the relationship of the coupling area with the low gain area along the antenna axis.

2. The Whistler Waveguide Transmission Model

The dip angle at high latitudes is so close to the vertical that the satellite is almost overhead the receiver. The beam path distance traveled is only slightly greater than the satellite's altitude. From Figure 4.2 we obtain a conservative attenuation factor of 15db for daytime. This could be several db overly pessimistic. Nighttime is obviously much more favorable for this type of communication, with a loss of less than 5db. A 15db loss is another 97% reduction of the coupled power. The total net loss up to this point is .995%, or 43.5db. This is the power ratio available to "uncouple" from the field line wave guide and "reradiate" to the earth's surface for reception at the termination point of the ray trace. The power summary is as follows ("Pu" is the uncoupled power in the lower ionosphere for reradiation to the earth's surface):

$$Pu = .03 * Pc$$

$$Pu = Pc - 15db$$

$$Pu = .00004 * Pt$$

$$Pu = Pt - 43.5db$$

3. The Uncoupling or Reradiation Model

The process of absorbing or releasing energy in the whistler waveguide tubes occurs within the ionosphere, but low enough so that the normal attenuation of the D layer for frequencies below the critical plasma frequencies and the gyro frequencies does not occur. The lower ionosphere is where energy is absorbed into the whistler mode from electromagnetic disturbances that originate on the ground (such as lightning), and where energy can be (re)released from sources at the other end of the field line. The whistler mode release area can be treated as due to multiple point wave front sources at an altitude of roughly 150km (the bottom of the F layer). The power uncoupled from the field line will propagate outward within the same 20 degree cone. The whistler transport mode is reversible in path and process, so any point on the earth within 20 degrees of a specific field line can couple to it. Therefore, from the surface to 150km, this area is considered to be illuminated by reradiation energy uncoupling from the field lines. From an altitude of 150km and an angle of 20 degrees, an extra 50km in radius can thus be added to both sides of the regular whistler footprint that would be formed as the beam transited through the the ionosphere, down to the Earth's surface. The size of the primary beam footprint can again be approximated geometrically. Rephrasing: the total size of the primary beam will be 50km greater in radius than the directly illuminated beam radius due to the uncoupling and reradiation effect. An even larger secondary footprint will be discussed later.

By referencing Figure 4.10, the radius width (east to west) of the primary footprint can be evaluated by multiplying the satellite's altitude in kilometers, times the tangent of 20 degrees (.36), and then adding 50km for the multipoint reradiation. The reradiation width is added to the ground footprint (vs the ionospheric footprint) mainly for model simplicity, but also because of the steep inclination of the rays that are still going to be following their original direction. Additionally, the ELF signal that penetrates to the ground will enter an earth - ionosphere waveguide that traps a portion of the signal and disperses it radially away. This Earth - ionosphere waveguide is the propagation method ground based ELF systems utilize. Figure 4.3 shows the attenuation rates for that system. This ground hopping will create a weak secondary footprint around a satellite primary footprint. Refractive effects will also spread the primary signal in the ionosphere before it reaches the ground, and the reradiation submodel allows for that refraction. A summary of the Primary Lobe Width (PLW) is as follows:

Primary Lobe Width = Altitude(.36)(2) + 100 = width km

PLW @ 300km of altitude = 310km wide

PLW @ 500km = 460km

PLW @ 800km = 670km

PLW @ 1000km = 820km

A secondary lobe can readily be expected to form from alternate paths that previously uncoupled energy may have found. This is analogous to the side lobes of typical antennas, they are there because of inefficiencies of the system (aperture, refraction, reflection, etc...). The secondary lobe can also consist of all the energy that eventually penetrates to the surface, but which gets caught in the earth - ionosphere wave guide. A secondary footprint 50% wider than the primary footprint (at one-forth the power, 6db down) is not untypical in communications systems. Given that the wavelength is on the order of 100km, this is only few wavelengths wider than the primary beam width. Again, a 6db loss would occur from only a few hundred kilometers of travel in the earth - ionosphere waveguide from a ground based ELF system. This same philosophy will be applied to the secondary lobe diameter. The radiation that penetrates to the ground, and is not immediately absorbed, will be trapped in the Earth - Ionosphere waveguide, expanding out to one and a half times the primary footprint. Beyond this distance, it will be assumed that the signal strength will have been attenuated below usable levels to be received. Summary of the Secondary Lobe Width (SLW):

Secondary Lobe Width = (1.5)PLW = width km

SLW @ 300km antenna altitude = 460km wide

SLW @ 500km = 690km

SLW @ 800km = 1000km

SLW @ 1000km = 1230km

The height, or north-south length of the beam footprint, can be evaluated while looking at Figure 4.8. The southern extent of the footprint will be near the satellite's nadir, with the northern extent defined by the leading edge slant ray departing the antenna at 30 degrees from the vertical. Reradiation will add another 50km to each side of this dimension. The altitude times the Tangent of 30 degrees (.58), plus 50km, is the primary footprint radius. Summary:

Primary Lobe Height (PLH) = Alt.(1.155)+100km = height km

PLH @ 300km altitude = 450km high

PLH @ 500km = 680km

PLH @ 800km = 1020km

PLH @ 1000km = 12500km

The secondary footprint height will use the same logic as the secondary footprint width:

Secondary Lobe Height (SLH)= (1.5)PLH = height km

SLH @ 300km = 675km high

SLH @ 500km = 1020km

SLH @ 800km = 1530km

SLH @ 1000km = 1875km

Figure 4.11 shows the footprint as it would probably be on the earth, and roughly defines its dimensions as a function of antenna altitude (h). The primary footprint illuminated on the earth from the main beam lobe is an ellipse, with the minor axis oriented east-west and the major axis (35% longer) north-south. The secondary footprint will also be an ellipse with the same orientation, but 50 percent larger than the primary. The earth is not flat however, but curves away from the satellite. The effect on the footprint is the same as shining a flashlight at a tangent near the perimeter of a basketball. The circle of light becomes elliptical, with a tear drop affect. The major axis in this case becomes even more elongated.

4. Primary Coverage Area

The area of the primary footprint is approximated by the area of an ellipse. It is expected that the derived footprint sizes are conservative by design, and that actual coverage areas will be larger. Based on the above major and minor axis, the following minimum square meter areas should be expected for a given altitude:

Primary Footprint Hot-Spot Size:

300km altitude : 110,000 square km

@ 500km : 240,000 sq. km

800km : 520,000 sq. km

1000km : 800,000 sq. km

Secondary Footprint "Warm-Spot" Size:

@ 300km : 240,000 sq. km

500km : 550,000 sq. km

800km : 1,200,000 sq. km

1000km : 1,800,000 sq. km

5. Illuminated Footprint Power Density

Now that the size of the signal footprint has been determined, and the coupled signal power delivered to that area is known, the proposed signal energy density can be determined. Total transmitted power attenuation (based on 1000km of travel) was 43.5db. The power that reaches the earth in the main beam is .004% of the original radiated energy. By taking a simple ratio of .00004Pt and dividing it by (.24 X 10E6), for an altitude of 500km, the order of magnitude solution is 10E-16 watts per sq. meter (-160db), for a 1 watt transmitter. If the antenna were radiating

10,000 watts, then the surface energy density should be on the order of 10E-12 watts (picowatts) per square meter. If "Pi" is the incident power (the uncoupled power spread over the illuminated footprint) then:

$$Pi = .00004 * Pt$$

$$Pi = Pt - 160db$$

This value can be compared to the attenuation factor for present ground based ELF systems. From previously referenced figures it was noted that the signal loss for a pure earth-ionosphere waveguide would be around 25 - 30db per 1000km (daytime). For a world wide ground based ELF system, propagation paths of 6000km, or more, would be typical. The signal loss due to the path loss attenuation alone would be 150 - 180db, or 10E-15 to 10E-18 below original intensity. Other losses to be added to this would be coupling losses and spherical spreading as the radiated wave expands out in all directions. At best, a ground system 100 times as powerful as a spaced based transmitter could form the same link. At less than optimum, it may take a ground station 1000 times, or more, as powerful to do the same job. Of course, the ground station has essentially unlimited energy resources, and can cover a much larger area, continuously. It is expected that a 10,000 watt satellite could downlink as much energy to a receiving antenna being trailed behind a submarine in the arctic, as a 1 Megawatt ground station could. It would also be more survivable in performing that mission.

The actual power received by an antenna trailed at depth by a submarine will be less than the surface incident power. Skin depth refers to a frequency and medium dependent depth in which signal intensity has been reduced to 1/e, or 37%. For seawater, the skin depth is between 36 and 100 meters at ELF; ice has a skin depth in the thousands of meters (essentially transparent when compared to seawater). A submarine can receive a signal just as well at a depth of 100 meters as it can at 100 meters below the bottom of a very thick ice formation. At a depth of two times the skin depth, the transmission factor is the skin depth squared, for seawater: 14%.

6. **Received Signal Voltage Level**

The power (P) that a dipole antenna picks up can be converted to a voltage signal level (E) from (P = E**2/377). The free space watts per sq. meter Poynting vector produces a volts per sq. meter signal strength in an electric field. This conversion is for ideal circumstances, but rounding down will allow for margin in the model. A power incident magnitude of 10E-12 watts / sq.m (for a 10kw transmitter) will produce 20 microvolts per meter of trailed antenna length. An ELF antenna 1km long, should be able to generate signal levels in the tens of millivolts, well within the capabilities of present day technology. Increasing the depth of the trailed antenna to several multiples of the skin depth still allows millivolt signal levels.

7. Sweep Rate and Swath Coverage

The orbital period for the satellite is around 100 minutes, varying from 90 minutes at 300km to 105 minutes at 1000km of altitude. Though the satellite can not physically orbit along the 65 degree north line of latitude, its ground speed while transiting this area of the world can be approximated by dividing the circumference of the earth (40,000km) by the orbital period of 100 minutes, for a sweep rate of 400km per minute. This is based on near circular orbits. At 1000km of altitude, 4 minutes of communications time should be possible using the conservative footprint sizes. Two and one half minutes of that time would be within the primary beam. Unless actual tests can prove a longer communications time, this short time interval could prove restrictive for this program. However, offsetting the short coverage interval is the rapid revisit time for the same satellite, within 90 minutes. The overhead times are also highly predictable and regular. If a 50% window time is desired, a constellation of 12 satellites would be necessary to cover each area of operation, based on a 10kw transmitter. On the northern most extent of each satellite pass, 60 degrees of east - west coverage should be possible, 30 degrees either side of the northern limit. At 65 degrees north, one degree east - west is about 47km wide; sixty degrees of swath is 2800km. The swath height still remains as the hot spot height. A constellation of 24 satellites divided into 2 orbital planes could cover both GIUK and the Bering Sea (or Straits) 50% of the time, for a swath also 60 degrees of longitude wide.

D. NOISE AND INTERFERENCE

Noise levels in the ELF ranges are relatively higher than in other communication bands, but ELF has its own advantages. There are two continuous sources of noises, both delivered along the whistler mode field lines: reciprocal noise transmitted from the opposite hemisphere (the field line's complimentary position); and charged particle oscillations along the field lines several earth radii away. For complimentary electromagnetic noise sources, the southern hemisphere has little activity. Complimentary positions are in the open ocean just north of the antarctic. Though this area is meteorologically very active, due to the lack of land to induce vertical disturbances in the atmosphere, there is apparently little lightning. The farther from the equator one travels the less the electrical atmospheric emissions. The motions of electrons and protons along the field lines produces a continuous broadband hiss which increases in the lower frequencies. It is recommended that studies be dedicated to evaluate high latitude ELF noise, and how it might interfere with whistler mode communications. [Ref. 27: pp. 10-20 to 10-63].

Most disturbances that disrupt communications systems affect ELF systems less because the propagation mode and wave guide paths insulate ELF from much of the variability in the ionosphere that can be caused by ionospheric storms and other Sudden Ionospheric Disturbances (SID's). Some SID's that can have interfering effects are: Sudden Phase Anomalies, Sudden Enhancement of Signals, Sudden Enhancement of Atmospherics (thunderstorms), and Polar Cap Absorptions. The lower the frequency, the less the interference from SID's. The variances of energy paths in the transport mode may produce pulse stretching of the signal as different elements of the signal arrives at slightly delayed times [Ref. 30]. Reflection of the signal from the opposite hemisphere will produce ghost signals at much reduced intensity levels.

E. SELF-POWERED GENERATION CAPABILITIES

Driving the tethered antenna in a semi self-powered mode has several advantages. By pumping electrons alternately between two ionospheric charge sinks (shells at different altitudes) the efficiency of the antenna within a conducting plasma increases, and antenna impedances are more controllable. Additionally, the conversion of momentum kinetic energy into electromotive force on alternate half cycles in the transmission phase, efficiently conserves critical power supply mass during peak transmission power demands. Depleted energy storage systems can be recharged by solar panels, or other low power continuous duty systems, during the off duty cycles.

The maximum self generated power ability of a tether can be easily calculated, as will be shown. As previously explained, the the induced voltage is a cross product of velocity (v) and field strength (B), dotted to the tether direction (l), times its length (L). An orbit with zero inclination produces the the maximum potential because the velocity vector is perpendicular to the meridian plane containing the the field line. With perpendicular vectors, the solutuion is a straight forward v*B*L. A conservative value for the orbital velocity minus the geomagnetic field velocity is 7.2 km/sec. The tether direction will always be down. Field strengths vary from .20 to .50 Gauss at 500km of altitude over various parts of the Earth. Field strengths vary more by latitude than by altitude.

As the inclination increases, the self generated voltage decreases because of the cross product. The tether velocity vector is not perpendicular to the field lines it cuts. As the tether reaches the most northern latitude of its orbit (still at low inclination), the voltage level increases because the cross product is again perpendicular.

As the inclination increases further, the maximum voltage produced at the northern extreme begins to decrease because of the dot product. The magnetic dip angle increases, so it is no longer perpendicular to the tether axis. When the satellite is at its far northern latitude is also when the antenna needs the maximum power available to transmit its ELF signal. The dot product acts through the cosine of the dip angle. The magnetic field strength, at altitude, over the Icelandic area is read as .42 Gauss (4200 Tesla) from Figure 4.4. With a dip angle of 80 degrees, a tether of 1km will produce [(7200) * (.42 * 10E-4) * (1000) * cos(80)] = 50 volts per kilometer. A 10km tether conducting 10 amps will produce 5 kw of power, over Iceland. A 20km tether can produce 10kw here.

It must be noted here that tether self powered generation levels are the same as the transmission power levels. Tether power is only injected into one - half of the phase cycle, and comes from orbital kinetic energy, but internal power supplies inject an equal and opposite current into the tether during the alternate phase cycle. The internal voltage supplies must be twice the tether generated voltage in order to overcome the tether potential, and still produce the same current level in the opposite direction. Current levels need to be the same in both directions to reduce signal distortion and impedance effects. Twice the voltage for the same current is twice the power, but over only half of the cycle. So, for a desired transmission power of X watts, the tether should generate voltage and current for X watts, the internal power supplies should generate X watts continuously, but 2X watts intermittently for the 50% cycle time within the alternating cycle that the tether is "resting" and getting its "microboost". The operational cycle is complex, but necessary. By allowing the tether to be self powered, antenna efficiencies are greatly increased (v.s., 100% on board power 100% of the time).

Ohmic losses of the cable permitting, transient bursts of higher currents may be necessary at times. A temporary increase to 20 amps in a 10km tether increases tether power (and transmission power if internal supplies can handle the surge) to 10kw. A 20km tether can be boosted to 20kw. Sustained high power level durations are a function of cable temperature and heat dissipation capability of the cable. Fortunately, total transmission time in a normal configuration is only on the order of minutes. By playing with the transmission power as a function of time, and footprint location, a broader effective footprint can be created. By boosting the transmission power (by boosting tether current over normal levels) while the secondary footprint is over the receiver target, and then reducing power when the primary hot spot is over the receiver, the communication window is much expanded and tolerable cable temperatures can be tailored. Tailored power boosting should be able to increase the the duty cycle coverage of an operational area to 75%, up from the nominal non-boosted 50% coverage.

If the peak self powered current exceeds the current limits of the on board supplies, that are necessary to reverse drive the cable antenna on the opposite phase, then the electromotive drag will be greater than the electromotive boost, and the orbit will decay. The orbit will have to be reboosted during the system's off duty cycle. If the fixed, on board, power generation sources are limited in capacity, and the energy used to reboost the system is not available to recharge the energy storage systems, then possibly degraded performance will be experienced on the next transmission duty cycle. Obviously, trade-offs abound throughout this system. Another notable trade-off an operator must consider is the timing of the broadcast. At night, the attenuation level is drastically reduced, but the satellite is in shadow and cannot utilize its solar cells. Solar panels are available in the daylight for power production, of course, but the path loss attenuation factors are much higher.

V. TETHER MECHANICS

A. ORBITAL DEBRIS AND SEVERING

The near earth space environment is increasingly being filled with objects from man's activities in space. Aside from the intentional satellites in orbit, unintentionally formed satellites comprise a mass spectrum from micrograms to kilograms. These are largely the result of rocket explosions and collisions. The population density of debris objects increases as the object size decreases. Below diameters of 1mm, the micrometeoroid population exceeds man made particulate debris. Over time the debris population is increasing, due to hypervelocity collisions and the continuing addition of more material from space operations. Debris particle density is sufficient to be of concern in designing the tethered antenna cable. A particle of enough size (mass) can sever a small diameter cable. Figure 5.1 [Ref. 31: p. 359] graphs the projected debris flux for the 1995 space environment. The vertical axis is flux, impacts per year per square meter area. The horizontal axis is particle diameter, in centimeters. The graph is log-log and the lines show the the cumulative flux for all debris greater than or equal to the selected diameter. The graph is courtesy of D.J. Kessler, of NASA Johnson Space Center.

As can be seen from Fig. 5.1, the probability of a hit increases dramatically at small diameters, indicating that a minimum diameter cable should be selected to survive a satisfactory lifetime before it is severed. A one square meter area has a probability of roughly 3X10E-3 (per year) of being hit by particles larger than 1mm, and a probability of 10E-4 from those larger than 3mm. The Small Expendable tether Deployment System (SEDS) [Ref. 32] report to NASA argues that a tether can be cut by all particles larger than one - third of the tether diameter. Therefore, a 1mm particle can sever a 3mm cable, and a 3mm particle a 10mm (1cm) cable. A 3mm diameter cable has a cross sectional area, per 1km of length, of three square meters; a 1cm cable of 1km length has ten square meters. The probability that a 10km long cable would be severed in ten years would be: 3mm cable = 90%; 10mm = 10%. The expected maximum lifetime for a 3mm cable would be 11 years, and the 1cm cable would be 100 years. Another report [Ref. 33] takes a much more pessimistic view, and with much more durable cable materials (steel and aluminum). In that paper, the authors believe a 1cm diameter electrical cable (with a steal core) of 10km length will have a 95% probability of surviving five years. By comparing these two evaluations it can be seen that for a long tether to just survive debris collisions from five to ten years, it must have a minimum diameter of between .6cm and 1cm (including the insulation). Determining a minimum servicable diameter is very important because doubling a cable's diameter will quadruple its mass.

B. TETHER STRENGTH

The diameter of a cable, in addition to its composition, largely determines its strength. A cable of great length will be quite massive. In the tether concept, the tether must not only support (i.e., be tensioned by) the end masses which are under opposite acceleration forces, but also the mass of the tether, whose acceleration tensioning forces also increase radially away from the system's center of mass. The gravity gradient tidal forces can become appreciable with long tethers. Temporarily disregarding a tether's mass, a tether 10-20km long will have tensioning forces of just under .01g exerted on it from the end masses [Ref. 34]. Worst case analysis would add total tether mass to the end masses without considering the tether's distributed gravity gradient accelerations across its total length. Actual loads will be discussed shortly.

C. TETHER MASS

Tether mass becomes significant as diameters over 3mm are used. Tether cables of 2 to 3 millimeters have typically averaged about 7 to 8.5 kilograms per kilometer [Ref. 35]. These have been low stress kevlar wrapped wires. Increasing the diameter to just under 1cm, and allowing for high tension materials that weigh more and a conductor thick enough to pass several tens of kilowatts, suggests a tether mass of about 100 kg/km. A 10km conducting tether could easily be 1000kg. The volume that this 10km cable displaces is one cubic meter, but the volume of the deployer mechanism and spool would be at least two cubic meters. The spool would be around two meters in diameter, with the drum one meter in diameter and one - half meter long. A 20km cable could use a drum / spool one meter long. This is a very manageable size for a satellite and its launch vehicle.

This estimate for tether mass aligns closely with a study by Dr. McCoy in which he outlines requirements for a 10km - 20kw tether motor / generator. His reference system uses a ten amp tether current through a 6.5mm wire, is rated at a continuous 20kw, and has a peak power capacity of 125kw. His tether mass, including the argon gas supply for the hollow cathode assembly, is 1200kg. Although this system is highly efficient electrically, it allows a seven degree bowing of the tether cable because of less than ideal structural mass relationships, which may not be acceptable when using the tether wire as an antenna. Figure 5.2 plots the relationship between the maximum desired tether power capacities and corresponding minimum required tether mass, for a stable tether configuration. This chart is designed to be used for a tether as a motor / generator, but it can be used as a guideline to provide upper and lower bounds on system considerations for a tether as an antenna. Note that driving a 10km long tether at 10kw is a very conservative expectation, and that increasing tether current well above ten amps is not only reasonable, but desirable (technology permitting). [Ref. 23].

D. TETHER BOWING

The tether stretched between the two end masses experiences oscillations due to forces exerted upon it. These forces can be due to dissimilar satellite motion of the end masses, translational and longitudinal forces, and electromotive forces from self powered operation or electrical boosting. The dynamo effect of the wire, as a generator or motor, is the largest force that may be impressed upon the system. The transient forces induce oscillations similar to that of a vibrating string. The steady state forces impress a bowing effect into the tether geometry. The degree of bowing is proportional to the power that is being produced or pumped by the tether, and to the mass of the system relative to the tether.

End masses that are small relative to the tether mass will be pulled together under high load conditions when the tether tends to bow the most. Increasing the mass of the system provides more inertia to resist the bowing tendency. Additionally, increasing the mass of the system increases total system momentum, providing greater resistance to orbit decay during high power production. Of course, it is also more mass that must be reboosted, but 80 to 90 percent of idle duty cycle time is available for the reboost. For a given tether power, greater mass allows more time between reboosts before the satellite pair is in jeopardy of terminally decaying out of orbit.

E. SATELLITE MASS

Tether mass is not the primary driving force determining what the total system mass will be, but it can be used to help establish minimum stable mass relationships. Surely there are much more important considerations that go into the total weight allowance like fuel, electronics, and energy storage devices. However, a simple relationship can help define a first guess satellite system weight. For the tether to behave as a vibrating string, firmly attached at both ends, and not have an excessive deflection angle (a lateral displacement much less than the tether's total length), which can pull the mother - daughter end masses together, then the tether should have a mass of no more than ten percent of the total system mass. The satellite's nontether mass can be more than nine times the tether mass (and may well have to be in order to have sufficient on board peak power capabilities), but it should not be much less than this. Ideally this mass should be evenly divided between both end masses, but it is reasonable to suppose that the maximum imbalance should be no more than a 30/60 split (with the tether as the other ten percent of the system mass). With a 30/60 split, one mass is obviously half as much as the other end mass, and only three times as massive as the tether. Using this analogy, a first guess total satellite system mass of 10,000kg is derived, apportioned between the tether and two end mass satellites. With the broad generalizations made here, an 8000kg - 10km tethered satellite, and a 12,000kg - 20km tethered satellite are also reasonable possibilities. The primary mass determining factors are the tether cable mass and the onboard power supply system mass.

F. TETHER DEPLOYMENT AND RETRIEVAL

The deployment of a tether is a fairly easy and stable process, mainly entailing providing an initial outbound kick along the local vertical, and then applying varying resistive friction forces to keep the unreeling cable aligned along the vertical. Growing gravity gradient forces on the tether accelerate its deployment. Rate control laws have been developed to determine the proper tension to maintain on the uncoiling wire [Ref. 36]. Retrieval is a very complicated matter, and an inherently unstable operation. When a tether is retracted, angular momentum is conserved, and if it is retracted too fast it could spin the tether and its subsatellite around the retrieving subsatellite. Small thrusters on the mother satellite can be used near the end of the retrieval to maintain tension on the tether, and prevent its flipping around the mother satellite [Ref. 37]. However, the same effect of using conserved momentum and translating it into transverse motion can be used to stabilize oscillatory motions of the tether. By pulling in or feeding out the tether at proper moments, oscillations can be dampened [Ref. 38]. In general practice, and for the purposes of this design, the tether will be deployed in orbit but it will not be retracted except for the purposes of active oscillation dampening.

The next chapter will put together all of the elements that have been covered, into the proposed tethered satellite concept. The last chapters will analyze program costs, draw conclusions, and make recommendations for further study and research.

VI. SUBCOM: THE PROGRAM

A. THE SATELLITE

1. Description

SUBCOM the satellite will be a mother - daughter satellite combination that is launched into orbit as a single unit, with a mass of between 8000 and 12,000 kilograms (4000 pounds). The total mass will be dependent upon final design capabilities, i.e., tether length and power production. Once in a circular, high inclination orbit (60 to 80 degrees), and at an appropriate altitude of around 500km (with a flexibility of choice between 300 and 1000km), the mother - daughter satellite will separate into two subsatellites, along the local vertical. The two subsatellites will be connected by a tether on a drum reel within the mother satellite. The daughter satellite will be unreeled upward as the mother satellite descends. Gravity gradient forces will accelerate the separation of the two satellites. This acceleration must be slowed by a frictional drag tether deployment program. The center of mass of the dual satellite system will remain at the original altitude. The tether will be approximately 10km long, with possible ranges of between 5 and 20 kilometers. At the end of the controlled deployment, the tether antenna will be in a gravity gradient stabilized, vertical orientation.

The mass of the tether will be on the order of 1000kg, and about 10% of the total system mass. The mother-daughter mass relationship (relative to total system mass) will range from 45%:45% to 60%:30%, with the mother subsatellite weighing equal to, or more than, the daughter subsatellite. With probable total differential gravity forces exerted across the entire tether length of .01g, and end masses of 9000kg, the apparent mass that the tether cable must support is 900kg, plus the apparent tether mass. Therefore, cable design must consider materials and construction that will allow a cable diameter of .6 to 1.0cm to support weights of 1000kg (1g weights). The tether will also be insulated against electrical leakage to the local plasma.

The mother subsatellite will be nearest the earth when the system is properly oriented. Being the most massive of the subsatellite pair (4500 to 6000kg), it will contain most of the main satellite systems. The systems installed on the mother subsatellite that are unique to this type of satellite are as follows: earth ground station communications, telemetry, data relay and storage; sun oriented solar panels and internal power generation, each capable of twice the tether generated voltage and no less than 10 kilowatts; three axis attitude stabilization; internal batteries capable of delivering at least 20 kilowatts of stored energy for 10 minutes; high amperage capacity hollow cathode and pressurized gas tanks to supply the hollow cathode; tether deployer mechanism; and high capacity digital switching device that can handle 10 to 20 kilowatts, and switch at up to 6000 times per second for at least 10 minutes; an intrasatellite communications system so that the mother and daughter subsatellites can communicate with each other (via small UHF antennas and transceivers on each subsatellite or digitally encoding an HF signal in thecable); an intersatellite communications system so each satellite pair can communicate with other satellite pairs; an apogee kick motor (AKM) for emergency manuvers or orbit decay control. The term AKM is used in the generic sense, regardless of where in the orbit it is fired. The AKM would primarily be used in case electrical tether reboost is not successful because of short term power shortages, extremely high inclination, or a highly decayed orbit situation. Also on board the mother satellite are all the auxiliary subsystems necessary for maintenance and operation of all satellites; systems not unique to this satellite, but common to all.

The daughter subsatellite will be the smaller of the two (3000 to 4500kg), and at the higher altitude. It will replicate some systems onboard the mother subsatellite on a smaller scale. The installed daughter subsatellite systems will be: one axis rotational stability attitude control system; solar cells one-third the capacity of the mother subsatellite panels; batteries also with one-third the capacity of the main system; an identical amperage capacity hollow cathode and gas bottle supply; an identical intrasatellite transceiver system; and a small backup earth communications system. Some of the systems' components and capacities must be distributed between both subsatellites in order to distribute the total mass and redundancy. The daughter subsatellite does not need much station keeping or attitude capabilities because of the stabilizing nature of the tether. Lateral and longitudinal positioning by the mother subsatellite will translate to the daughter along dampened cable angles and radial positions.

2. **Operation**

Operation of the satellite is simple. Ground stations will uplink via UHF all satellite control commands and the data relay information. The data relay information is the data that the satellite will be transmitting back down to the submarine operating areas. The data relay can be either downlinking a real time uplink channel, or a store and dump technique from burst uplink transmissions. The satellite will transmit only during the northern most orbital segments, an interval that lasts no more than 10 minutes out of a 100 minute orbital period. Normal satellite transmission duty cycles will be 10% on and 90% off. During the on duty cycle, transmission power will be provided by tether self powered electrodynamics for one half cycle of the frequency transmitted, and onboard systems will provide the power for the other one half cycle.

A digital switching system will switch current direction between the opposite polarity power systems at twice the rate of the frequency being transmitted. Intelligence (the data being relayed) will be transmitted by digitally delaying the polarity switch time. By differentiating between a time sync pulse and the received frequency phase switch, a primitive two state encoding can used to transmit data at a very slow rate, fulfilling the present role as a bellringer. Thus, the signal will not be truly modulated, but be digital pulse positioning about a carrier frequency that will be between 1khz and 3khz.

The on board power will come from sun oriented solar panels, batteries, and any other internal supplies that may be installed to boost power levels (such as RTG's or even dynamic nuclear generators if a massive system is designed for 100kw or higher levels). The size of the solar panels and batteries depend on trade offs. If solar cells are the primary power source for long term operation, then at a minimum they should be sufficient to provide permanent satellite internal power needs, plus the satellite transmission power level (for 10 minutes) spread across one half an orbital period for recharging the transmission batteries. Power transmission batteries are necessary because during the on cycle, half the transmission power must come from internal sources at a very high energy level. Ideally, it would be optimum to have solar panels large enough to completely supply this power requirement when sunlit. If transmission is on the dark side, then the only option is batteries or fuel cells. If batteries are used to match the self generated tether power, then solar cells have half an orbit (at least half the orbit would be sunlit) to replace all the power removed from the batteries in the previous 10 minute broadcast, about 35 to 40 minutes of recharging time. If the broadcast is being done in full sun light, then later battery recharging may not be necessary.

To keep the orbit from decaying, internal power (solar, battery, fuel cells, whatever) must match self generated power. This system does not create power, the conservation of energy applies. Solar power collected over 90 minutes (35 minutes at worst) is being deposited in batteries to be expended in 10 minutes. Self generated tether power comes at the expense of orbital energy, which in turn is redeposited from internal power in the opposite phase from which it is extracted. The orbit decays and is reboosted all in the order of milliseconds, during the on duty cycle powered transmission phase of 10 minutes. If internal power supplies can not match the self generated power, the satellite will exit the broadcast phase at a slightly lower orbit. In this case solar power must be routed not only to the batteries to recharge them, but also to the tether for continuous DC reboost during the off duty cycle. The system is flexible in its operating altitude range, and can function anywhere between 300 and 1000 kilometers. Higher altitudes allow more tolerance for orbit decay monitoring, and less atmospheric drag. Higher altitudes also permit larger footprints and longer illumination windows.

Changing the orbit altitude is an easy process. If time is not of the essence, simple electrical boost or drag can be utilized. Circularizing a slightly elliptical orbit is the same process, but boost and drag phases must be closely monitored. If an emergency exists and there is not time or energy for an electrical reboost, then the emergency AKM on the mother subsatellite must be used. The tensioned tether and daughter subsatellite will follow, though the process must still be done at a rate slow enough so that tether tension is not ever lost, or else an unstable condition may result, possibly snapping the cable when the daughter velocity becomes out of phase with the mother velocity.

Changing the orbit plane (rotation of the line of nodes) and inclination are not so simple but require standard propulsion packages on the mother subsatellite. The proceedures would be the same as utilized on standard satellites except the corrections should be slow enough to allow the daughter subsatellite to remain in a stable position relative to the cable and the mother subsatellite.

3. Trade-Off Analysis

Orbit inclination affects radiated transmission power. At low inclinations, maximum self powered tether voltages are restricted by the cross product, and at higher inclinations the dot product dominates (dip angle). Inclination also affects reboost ability, because continuous DC power pumped into the tether for reboost will be working against a field vector other than perpendicular. In a pure polar orbit, electrical reboost will not be possible, and an AKM will be needed. Reboosting at lower inclinations will be more effective than higher inclinations. The necessity of transmitting to operational areas high in the northern hemisphere dictate that the system should be designed for minimum reboost by increasing solar power and battery power.

Inclination indirectly affects the coupled power because at high inclination angles, in the northern operating areas, the magnetic dip angles are also very high. High dip angles mean less of the transmitted energy is efficiently coupled from the dipole antenna to the field lines. It is the coupled energy which propagates down the field line to the earth's surface.

Altitude does not affect the satellite performance as long as it remains within the 300 to 1000km altitude window. Higher altitudes will produce a larger footprint, longer illumination time (window), slightly wider swath width and height, but lower signal density.

The design power ratio between solar and battery capacity needs to be closely evaluated so that an optimum configuration can be obtained. As discussed earlier, there is a minimum solar requirement. The advantage to increasing the solar capacity is less reliance on battery use. If the solar arrays were large enough to supply the maximum continuous internal transmission power requirement (sunlit), then minimal recharging would be required and the risk of needing a reboost is slight. By increasing battery size, the maximum transmission power can be temporarily boosted above the self generated power to increase the radiated signal power. This will also have the effect of boosting the satellite's orbit. The excess energy can later be extracted and put back into the batteries. By maximizing both the solar arrays and the battery capacity, flexibility is increased, safety margins are increased, and management efforts are reduced. Higher transient power levels are also possible on a temporary basis. Energy storage systems and solar panels all have specific mass/kw, volume/kw, and initial cost/kw ratios. These ratios need to be compared to the operational requirements and the cost budget.

B. THE CONSTELLATION

1. Description

With a maximum coverage window of 5 to 10 minutes, depending on the altitude of the transmitter and how close the real system compares to the conservative model, and an orbital period of 100 minutes, the coverage gap for one geographic spot and one satellite is 90 minutes, plus or minus a few minutes. For 75% coverage (+- 25% due to estimations) there would need to be 12 satellites in the same orbital plane, equally distanced apart, for each swath area of 1500km by 3000km in the northern latitudes. If more than one operational area is to be broadcast too simultaneously, then another constellation of 12 satellites in their own orbital plane and inclination is necessary. Three geographic areas (GIUK, Bering, and Queen Elizabeth Islands) would require 36 satellites in three planes. Of course, if larger gaps in coverage can be tolerated, and if the satellites could propel themselves occasionally into other orbits for nonsimultaneous coverage, then many less satellites would be required.

Ground station support is hard to evaluate at this point of development. It is conceivable that sufficient communications assets exist to support this satellite program at present, with the addition of manpower and a command and control center. It is also possible that a full program of 36 satellites that are constantly decaying and reboosting would involve considerable managerial effort to support, requiring dedicated ground stations. The final satellite product will determine the ground station demands, obviously.

2. Operation

As sequential satellites of the same orbit plane pass over the desired coverage area, the communications responsibilities will be handed off just as with earthbound mobile car phones. In order to simplify instructions to the orbiting constellation, each dual-satellite combination should be in communications contact with each satellite just preceding it and following it. In this manner, a ground station command instruction can be passed up to any one satellite, and have it relayed to all the other satellites. As one satellite moves off-station from the swath area, it can signal the following satellite to commence broadcasting.

Ground station coordination to maintain the constellation's integrity will be significant. Unequal boost and drag factors will not only disrupt the common broadcast altitude of the constellation, but affect the overhead intervals, because different altitudes have different orbital periods. Minimizing the need to reboost greatly reduces the manpower and equipment asset base needed to operate the system.

3. Trade-off Analysis

Mission need and program funding will determine the number of satellites. The number of satellites will determine coverage gaps and the number of separate operational areas that can be broadcast to.

The next chapter will briefly examine program costs. The last chapter will be a summary and conclusions, recommending future work or studies.

VII. ESTIMATED PROGRAM COSTS

Estimating the cost for the SUBCOM satellite program is very difficult at this early stage, but some ballpark assumptions and educated calculations can give a feel of the cost. The source document that will be used is the" Unmanned Spacecraft Cost Model" [Ref. 39].

By examining current satellites, the satellite subsystems may be very roughly estimated as a percentage of total satellite mass. Satellites differ, of course, and surely this one will be very different, but comparisons with previous missions should provide a first approximation. SUBCOM will be broken down into seven very general subsystems that will have to be mission "all encompassing". The subsystem mass ratios were adjusted to include the peculiar properties of tethered satellites (i.e., tether mass allocation, etc...). Tabulated below are those seven satellite subsystems, and for each subsystem the estimated mass ratio as a percent of total satellite mass, the estimated mass in kilograms based on a 10,000kg satellite, and the 1g weight in pounds is given.

Table 2 will break down the costs of each of the subsystems based on their mass and associated dollar weighting. The first column will be nonrecurring costs in 1979 dollars, and the second column will be recurring costs

TABLE 1

SUBSYSTEM MASS RATIOS

SYSTEM	MASS RATIO	KGS	LBS
1. Structure	20%	2000kg	780lb
2. Thermal control	1%	100kg	40lb
3. Mission communication	20%	2000kg	780lb
4. Telemetry, tracking and control equip.	8%	800kg	320lb
5. Electrical power sys.	30%	3000kg	1180lb
6. Attitude control sys. and 3-axis AKM	20%	2000kg	780lb
7. Computer/Data storage	1%	100kg	40lb

per satellite in 1979 dollars. Nonrecurring costs refer to one time start up costs, independent of the number of satellites built. This is the design, development, testing, etc.... Recurring costs are the actual costs to build each satellite, based on the first unit cost. The costs for later satellites will be adjusted for an efficiency in learning curve. Subsystems one and two (structure and thermal control) will be combined for analysis.

The total one time nonrecurring development costs are approximately 100 million 1979 dollars, and the first unit production costs are approximately 50 million dollars. For a constellation of 12 satellites the total recurring costs will not be 12 times the first unit cost, but about ten times, because the learning curve decreases the production cost of follow on units. For a 12 satellite system then, the

TABLE 2

SUBSYSTEM COST ESTIMATION

SYSTEM	$ NONRECURRING	$ RECURRING
1&2. Structure and Thermal	$10M	$2M
3. Mission Communication	$20M	$14M
4. Telemetry, Tracking and Control	$14M	$7M
5. Electrical Power Sys.	$15M	$10M
6. Attitude Control and AKM $40M	$40M	$16M
7. Computer and Data Storage	$4M	$12M
Total 1979 Dollars	$103M	$51M

total recurring costs will be 500 million dollars. Total program costs are the sum of nonrecurring and recurring costs, or 600 million dollars in 1979. This is not 1979, but approaching 1990, and a rough inflation adjustment for 11 years compounded annually at 2.6% per year is a convenient 33%, or 800 million 1990 dollars. The average per unit cost of a 12 unit satellite production line is just over 65 million dollars per satellite. A full 36 satellite, 3 plane constellation, would bring per unit costs down to 55 million dollars per copy in 1990 dollars. Table 3 summarizes what has just been discussed.

This analysis did not take into account some important factors that have significant costs, but are extremely hard to estimate at this point. For the nonrecurring costs, the

TABLE 3

AQUISITION COST SUMMARY

Nonrecurring costs (rounded, 1979)	$100 Million
Recurring costs (12 satellites)	$500 Million
Total program cost (1979 dollars)	$600 Million
Inflation correction (1.33, 1990)	$800 Million

Aerospace Ground Support Equipment must be included; ten to fifteen million dollars is a first guess at 10% of total nonrecurring costs. Recurring costs will have two factors: Program Management at approximately two hundred fifteen million dollars per year to operate and manage the satellite program; and Launch Operations and Orbital Support at thirty to thirty-five million dollars per year to operate and support the 12 satellite constellation system over the 10 to 12 year operational life of each satellite. Therefore, additional costs are one time ground support costs of perhaps $15M, and yearly operating costs of $250M, in 1990 dollars. Table 4 summarizes program aquisition costs.

TABLE 4

1990 PROGRAM COSTS

12 Satellite aquisition cost :	$815,000,000
Yearly operating budget :	$250,000,000

VIII. CONCLUSION

A. SUMMARY

In this thesis, a conceptual design for an ELF/VLF satellite transmitter for communicating with submarines under, or near, the polar ice fields has been discussed. Downlink frequencies will be between 1khz and 3khz. Preliminary arguments established the mission need requirement for such a space based asset. By moving this communications link into space, a much more survivable transmitter may be obtained, and redundancy is increased. Transmissions will be more covert, with less chance of widespread interception, because the beam pattern is highly directional along the propagating field line. The directivity also focuses the signal pattern onto the earth's surface, increasing the illuminated energy density available for receiving antennas. With the increased signal strength able to penetrate a greater depth of water, and the increased coverage area this system provides in the far northern operating areas, submarine operations are enhanced and receiving periods are not going to be restrictive or vulnerable to submarine safety.

The proposed satellite is a 10,000kg, dual satellite pair that is connected by an antenna tether 10km to 20km in length. The satellite will be gravity gradient stabilized in a vertical orientation. It will have a high inclination orbit to bring it over the polar operating areas, and will pass overhead in an altitude window of 300km to 1000km. Through the unique properties of self-powered electrodynamic forces, and whistler mode propagation, the satellite will be able to generate a substantial amount of its own transmission power, and then be able to couple that radiated power along the earth's field lines to the earth's surface. Both of these special properties depend upon interactions with the geomagnetic field around the earth in a manner that no previous system has utilized. The success of the proposed system in fact depends entirely on these very unique, and particular, properties of space environmental physics.

The operating area communications swath size for one orbital plane is a shallow arc approximately 3000km long east-west, and almost 1500km north-south. All system studies were made using the most conservative analysis, assumptions, geometry, and models. With worst case assumptions made for all numbers, a feel for the program's success can be determined, since it is expected an operating system would exceed, by a wide margin, the limits of the research model. With that again pointed out, the hot-spot illuminated window will be well over 1000km high and 500km to 750km wide. A secondary widow from earth-ionosphere wave guide trapping will be over 1500km high and over 1000km wide. Overhead communication time will be 5 to 10 minutes per satellite pass, with a revisit time for the same satellite in 90 minutes. If a 7.5 minute window is used, a constellation of 12 satellites will provide 75% coverage time for that operational area. Coverage gaps would be just a few minutes until the next satellite passed overhead. For each operational area that is outside the 1500X3000km swath, a different orbital plane must be used, with its own complement of satellites.

The study baseline power projection is 10,000 to 20,000 watts of transmitter power. The actual power may vary from initial expectations, and is highly dependent on tether length and technology. Deviations are most likely to be upwards because of the conservative assumptions. Increased burst transmission power levels, by a factor of two or three on an intermittent basis, are also possible in the system design by temporarily sacrificing orbital energy. The efficient use and interplay of solar power, batteries (or other internal energy storage), and self generated tether power (orbital energy as an energy reservoir) allows for an amazing flexibility in energy management and an intriguing application for current technology.

Program costs are very hard to evaluate at this level of examination, but standard procedures in cost modeling can be used. This model produces a 12 satellite constellation aquisition total cost of $815,000,000 in 1990 dollars, for a per satellite cost of just over $65M. Ongoing program and system operations costs will be on the order of $250M annually. The operational life of the satellite is expected to be 10 years.

B. WHAT STILL NEEDS TO BE DONE?

There are so many areas of study that need to be examined more closely in this proposal that it is hard to begin mentioning the most important concerns. Probably the single greatest performance variance is the power that can be coupled from the antenna into the earth's field lines. Fortunately this is getting a lot of study at the present time by Denis Donohue, who works for Peter Banks at Stanford. He is studying coupling models and ray tracing patterns for a number of situations.

The following issues are recommended for further research and need to be studied in-depth:

1. Tether power production as a function of inclination and dip angle.
2. Modeling the Earth's field lines as per application to a spacebased ELF transmitter.
3. High and Low latitude ELF/VLF ray tracing.
4. Modeling the upper and lower ionosphere w.r.t. ELF wave propagation.
5. Tether survivability and debris hardening.
6. The use of multiple tethers on the same satellite pair.
7. High current hollow cathode assemblies.

8. ELF noise sources and levels.

9. Sixty Hertz harmonic interference.

10. Tether cables: materials, insulation, conductors, current capacity, heat tolerance, tension stress, and thermal cycles.

11. Kilowatt level, digitally controlled RF switches.

12. Short duty cycle, high density, energy storage systems.

13. ELF antenna radiation efficiency in a magnetoplasma.

14. ELF antenna impedance matching in a magnetoplasma.

It is recommended that a definition study satellite be developed that can test proof of principle operation, and collect data fields of various conditions. The primary payload of the experimental satellite will be test instruments. The test satellite will also be a tethered satellite, but the cable need only be 1km to 2km in length. Normal inclination orbits can be used, and propagation paths from its onboard ELF/VLF transmitter can be examined at receiving stations around the world. It is also desirous to include a free flying piggy-back satellite to study the local plasma, and field effects around the tethered satellite. Though dual satellite operations within close proximity of each other are complex, the data obtained would be invaluable in improving the effectiveress of transmitting antennas in ionized plasmas. The Soviets [Ref. 40] have recently announced a similar study for similar reasons.

Their tethered satellite experiment, with its free flyer subsatellite, will be in an inclination of 83 degrees, altitudes between 500km and 2500km, and will be using VLF transmission bands.

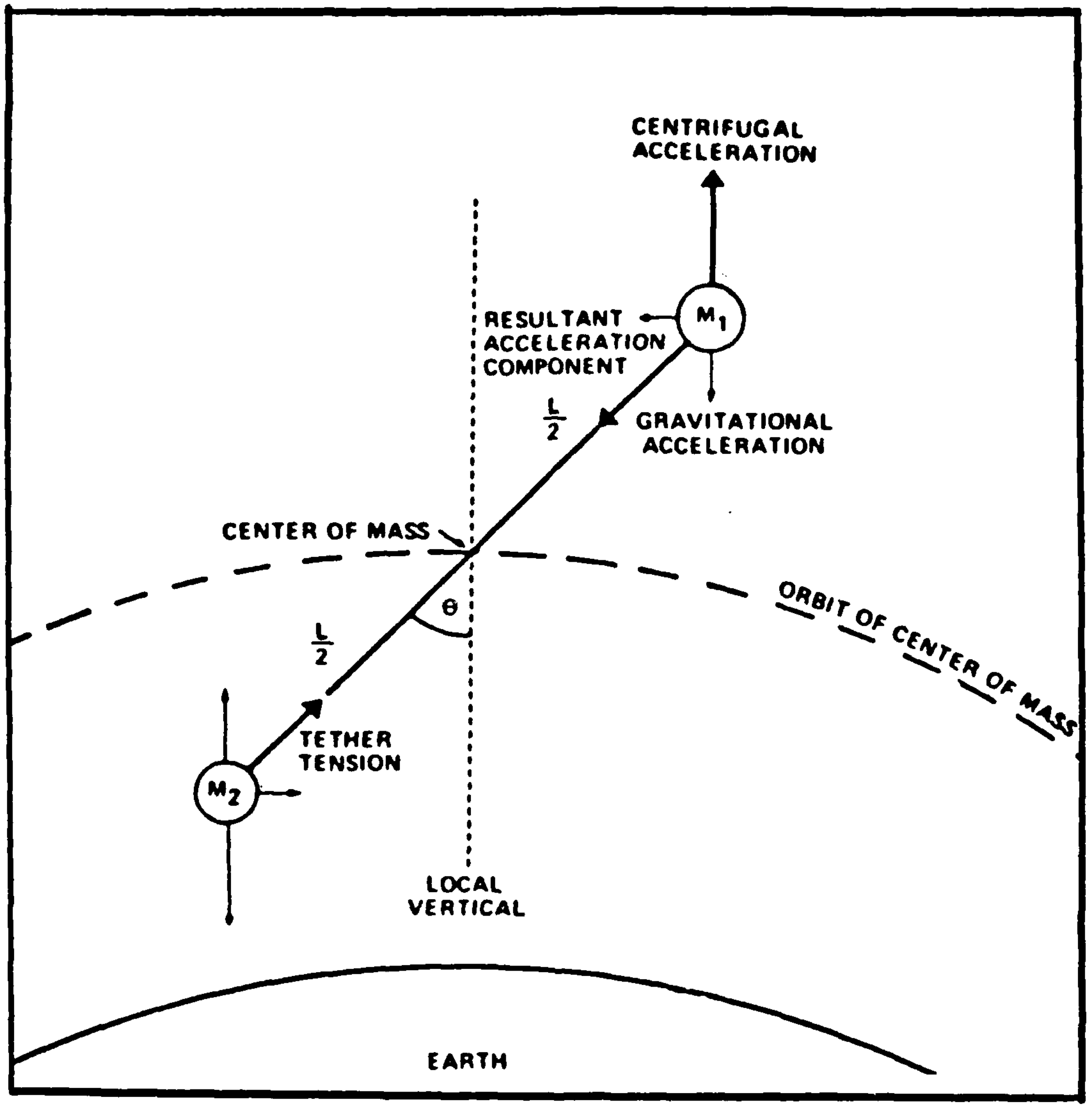

Figure 2.1 - Stabilizing forces acting on tethered masses [Ref. 12].

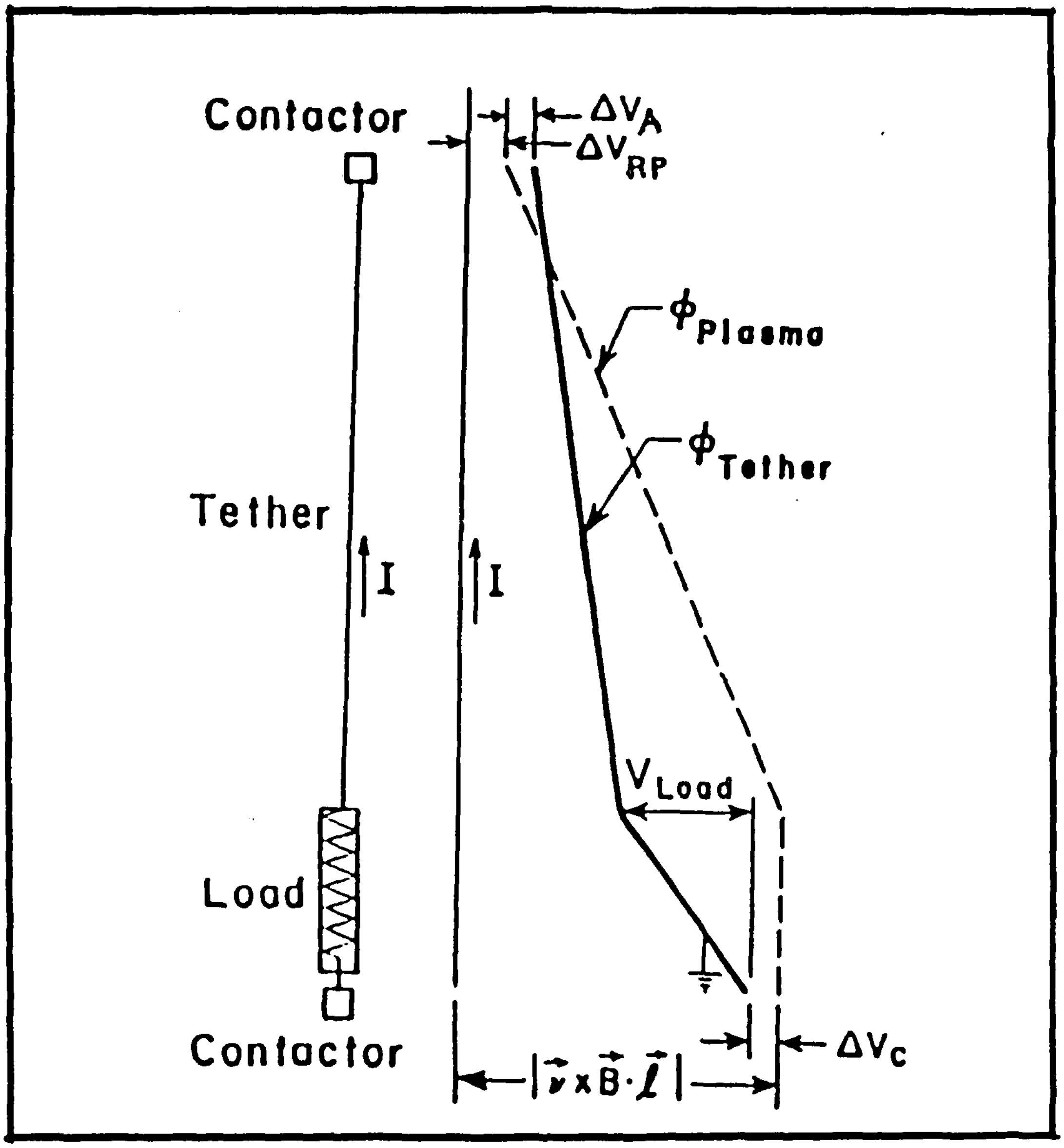

Figure 3.1 - Potential diagram for tether as a generator [Ref 20].

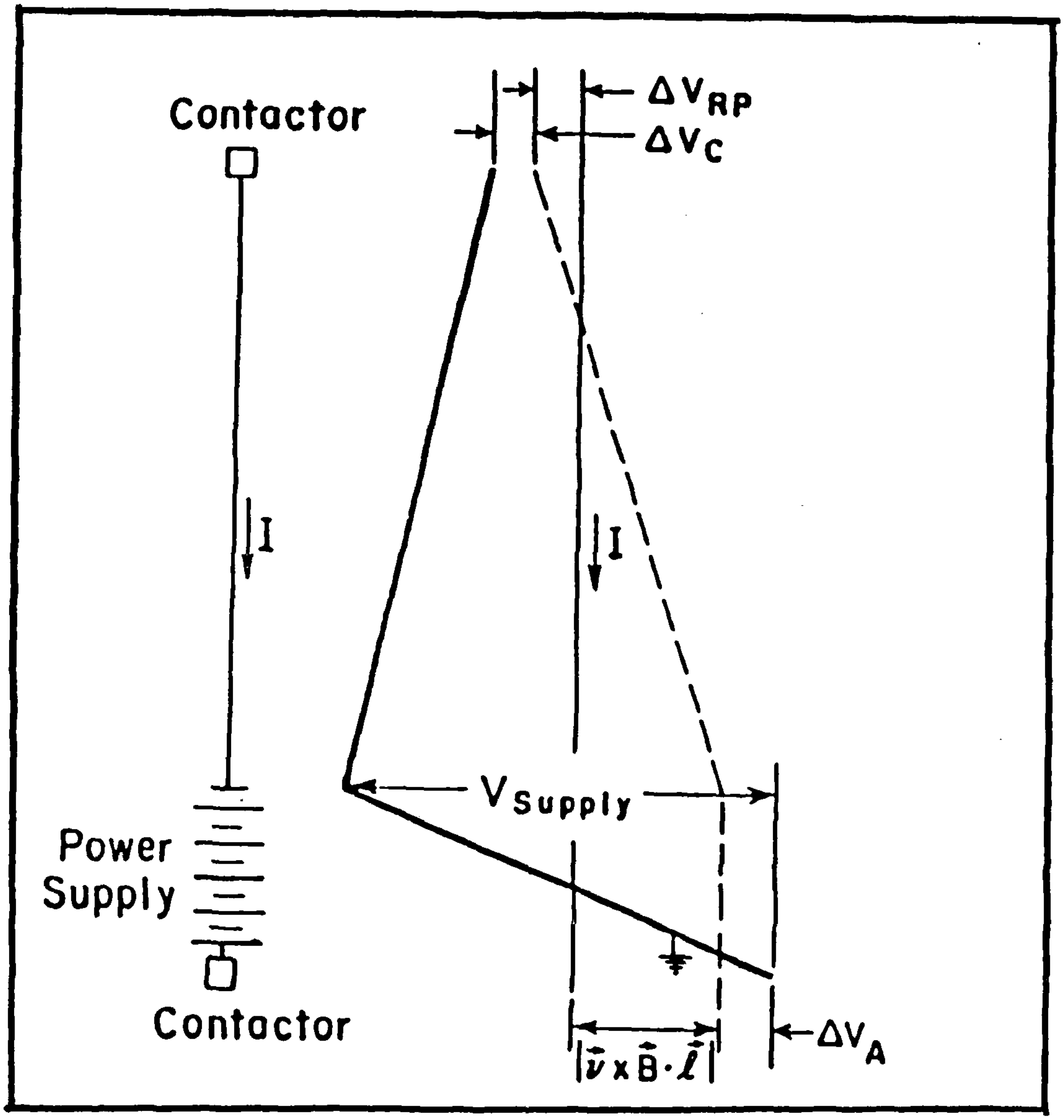

Figure 3.2 - Potential Diagram for tether as a thruster [Ref. 20].

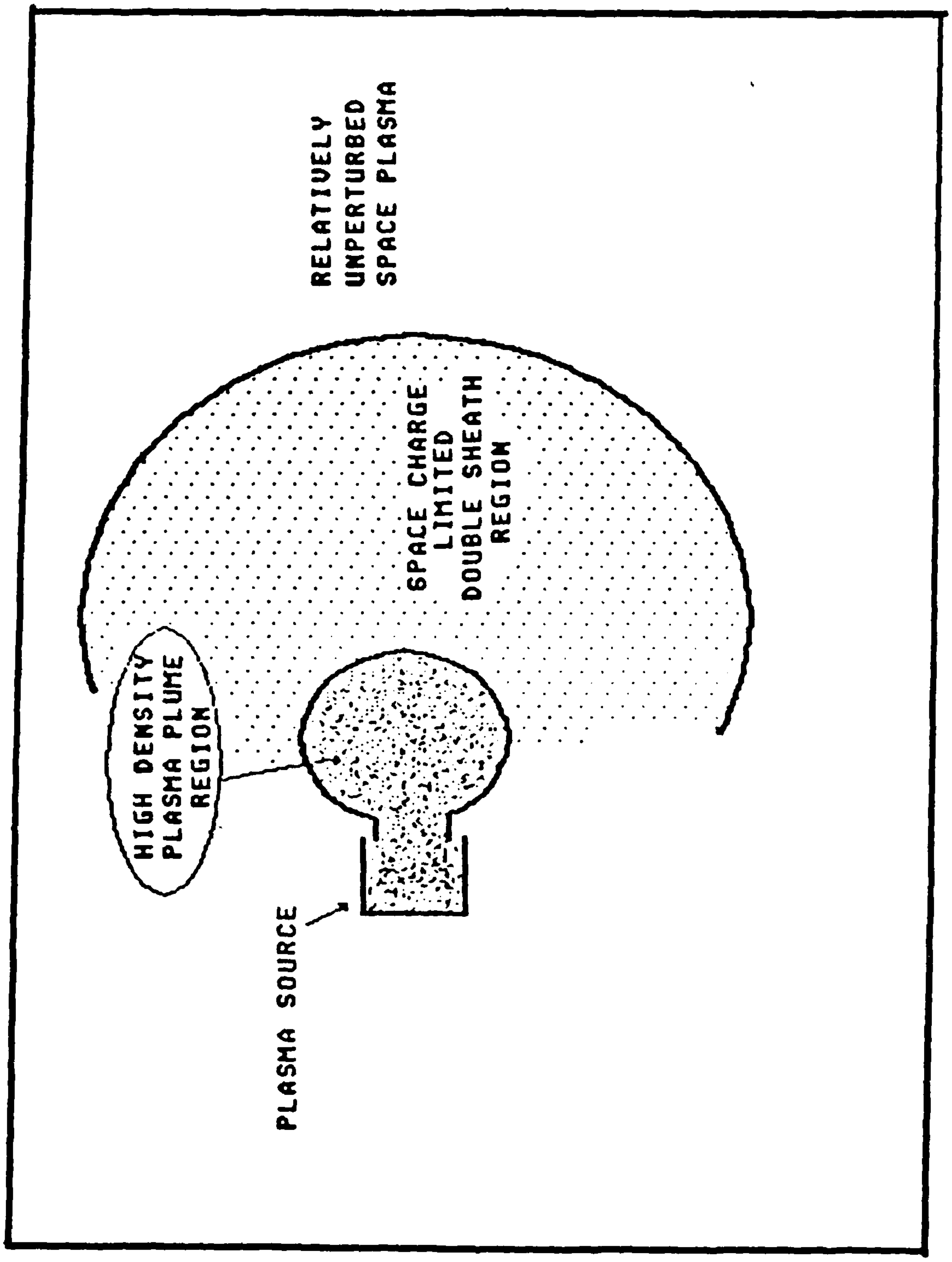

Figure 3.3 - Structure of contactor plasma plume region [Ref. 22].

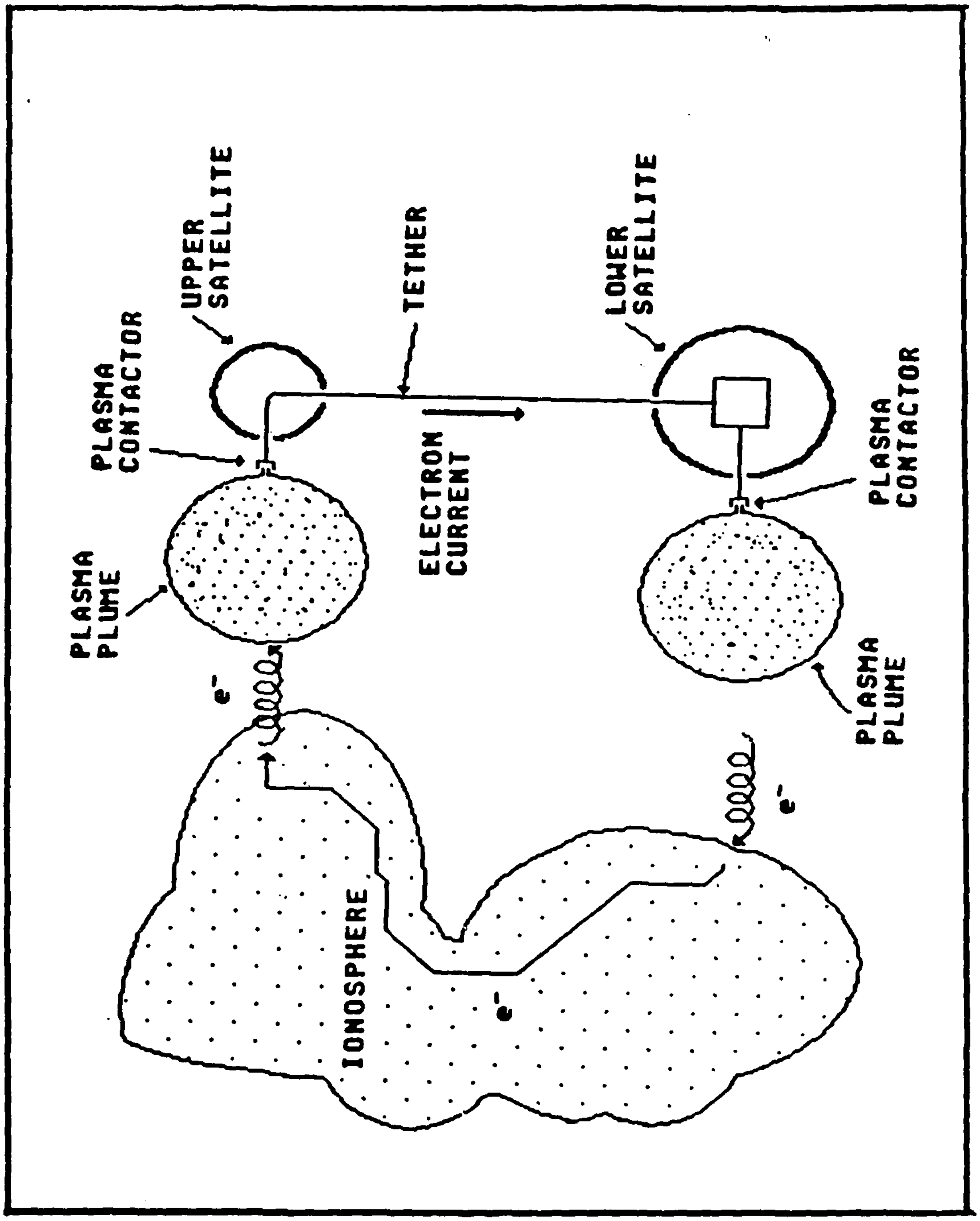

Figure 3.4 - Schematic diagram of electrodynamic tether system [Ref. 22].

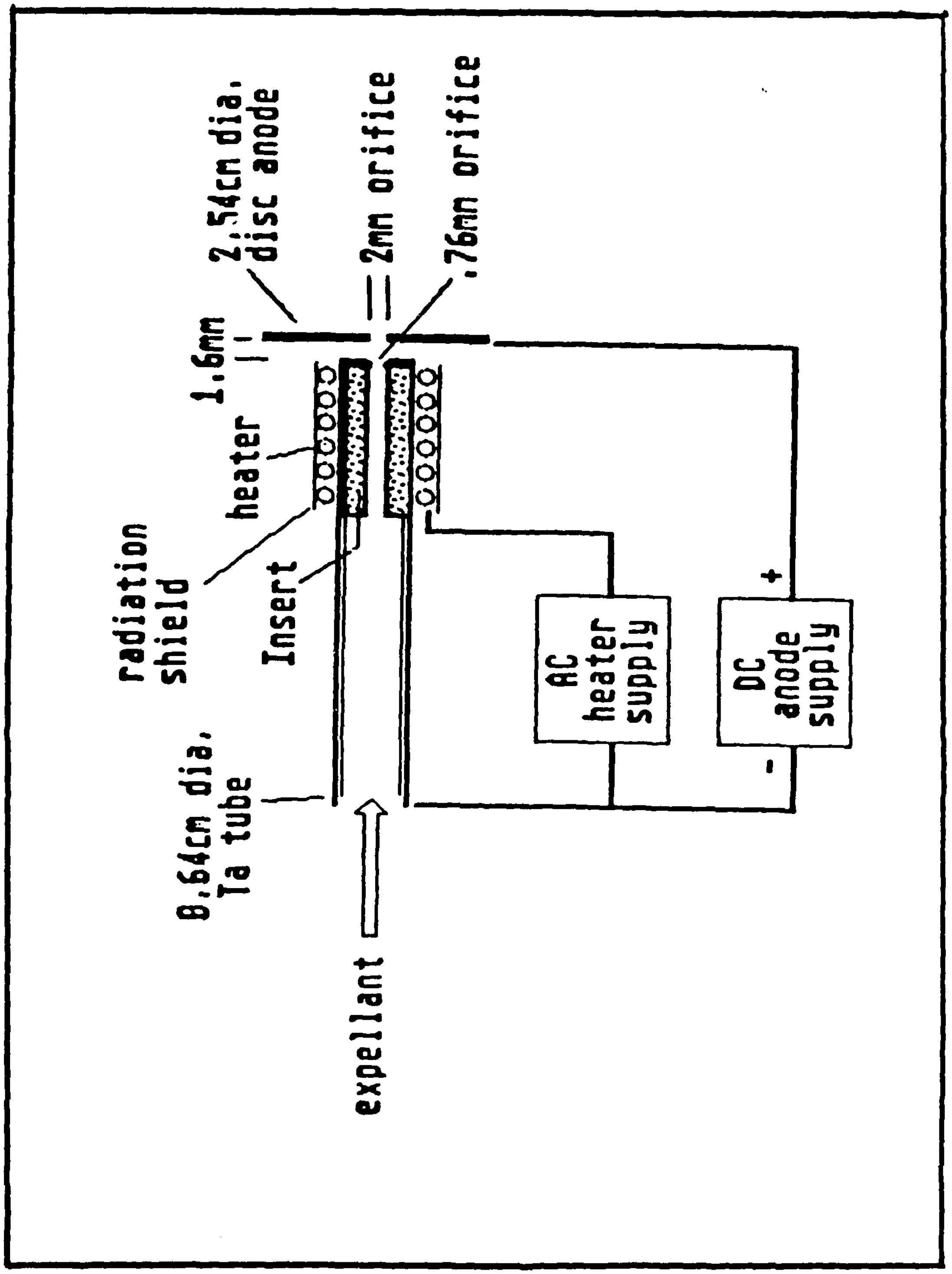

Figure 3.5 - Electrical and mechanical schematic of a hollow cathode [Ref. 22].

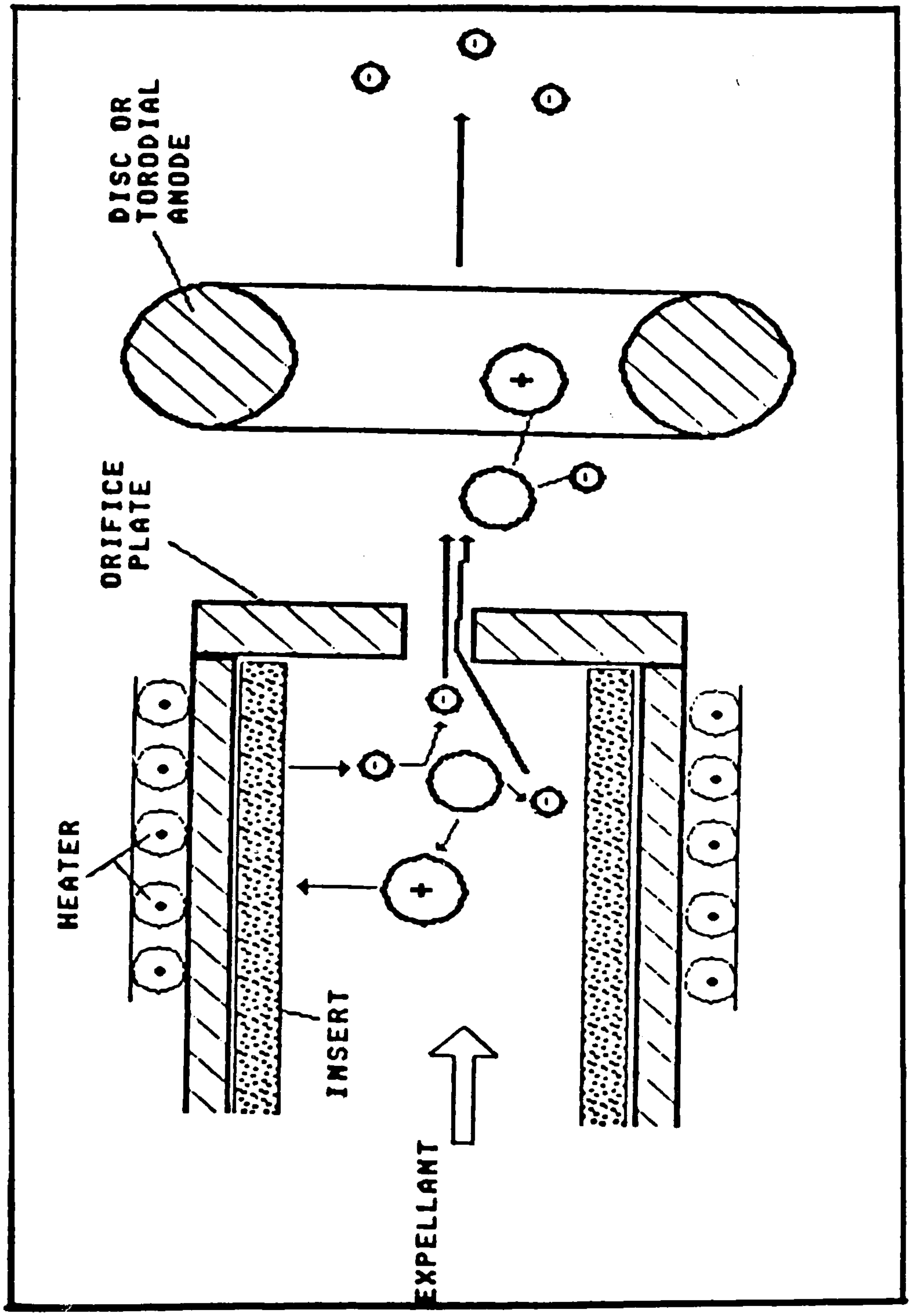

Figure 3.6 - Cross section of hollow cathode in operation [Ref. 22].

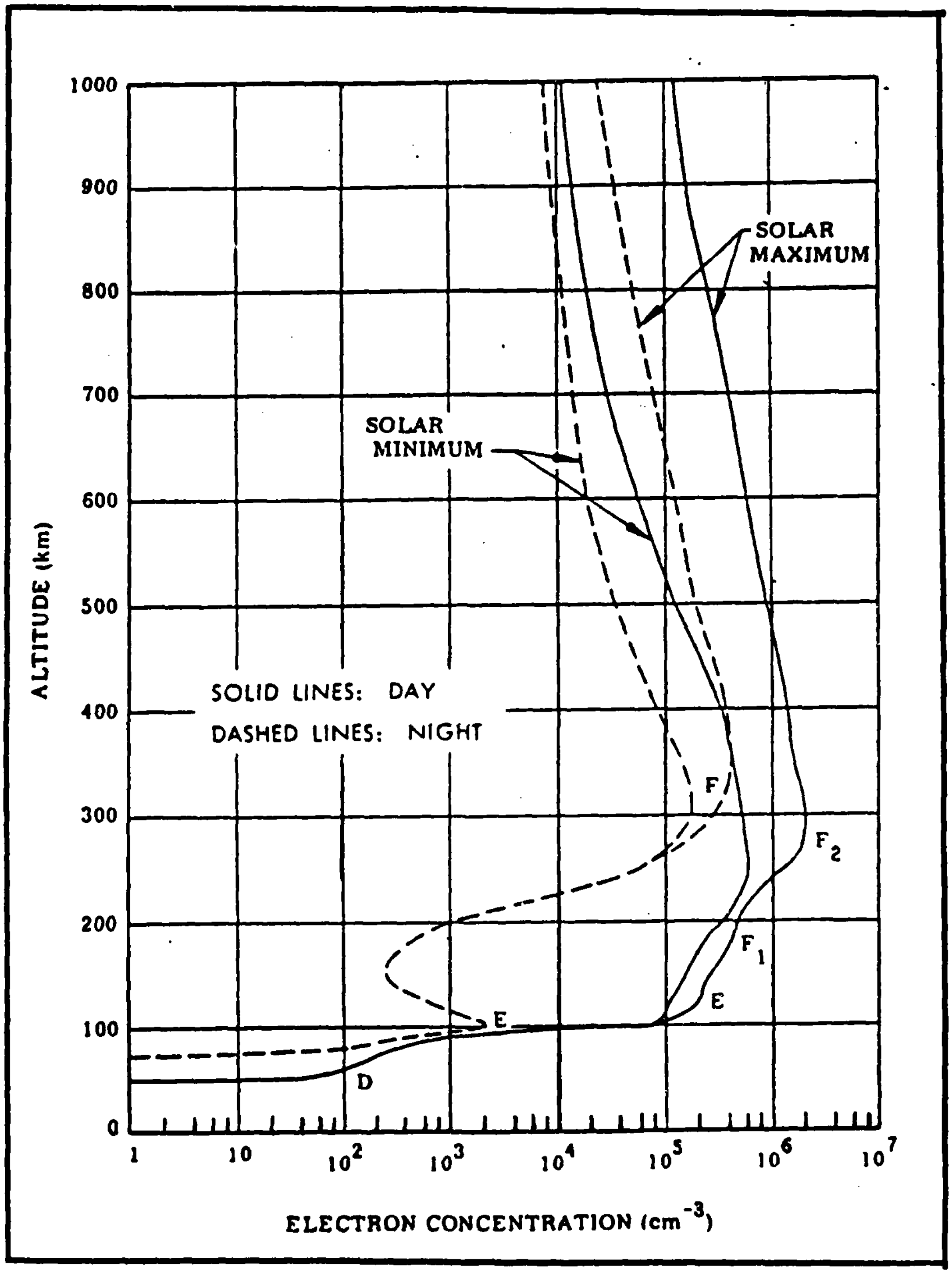

Figure 4.1 - Distribution of free electrons in the atmosphere as a function of altitude.

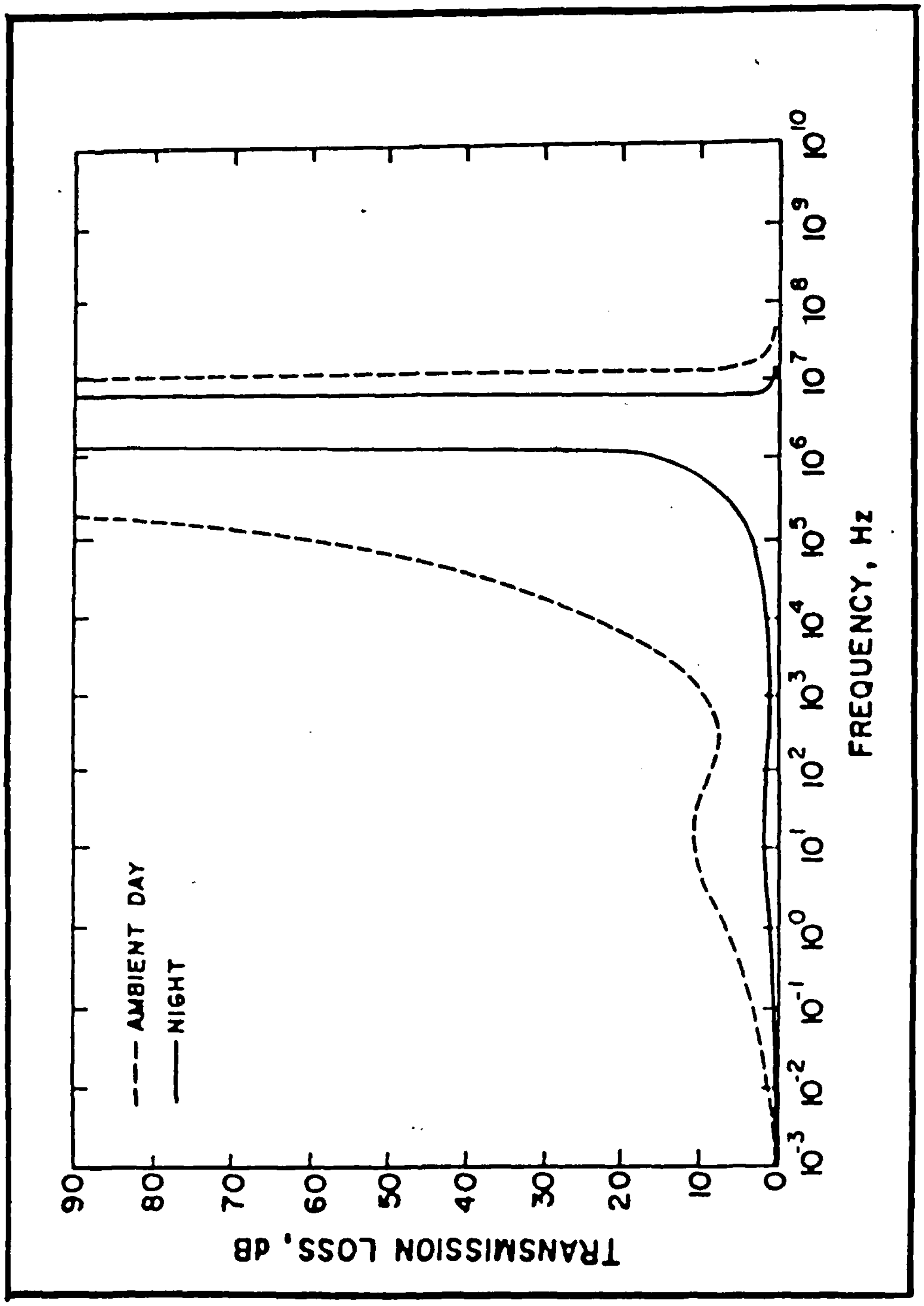

Figure 4.2 - Computed ELF ionospheric penetration losses [Ref. 27: p. 10-38].

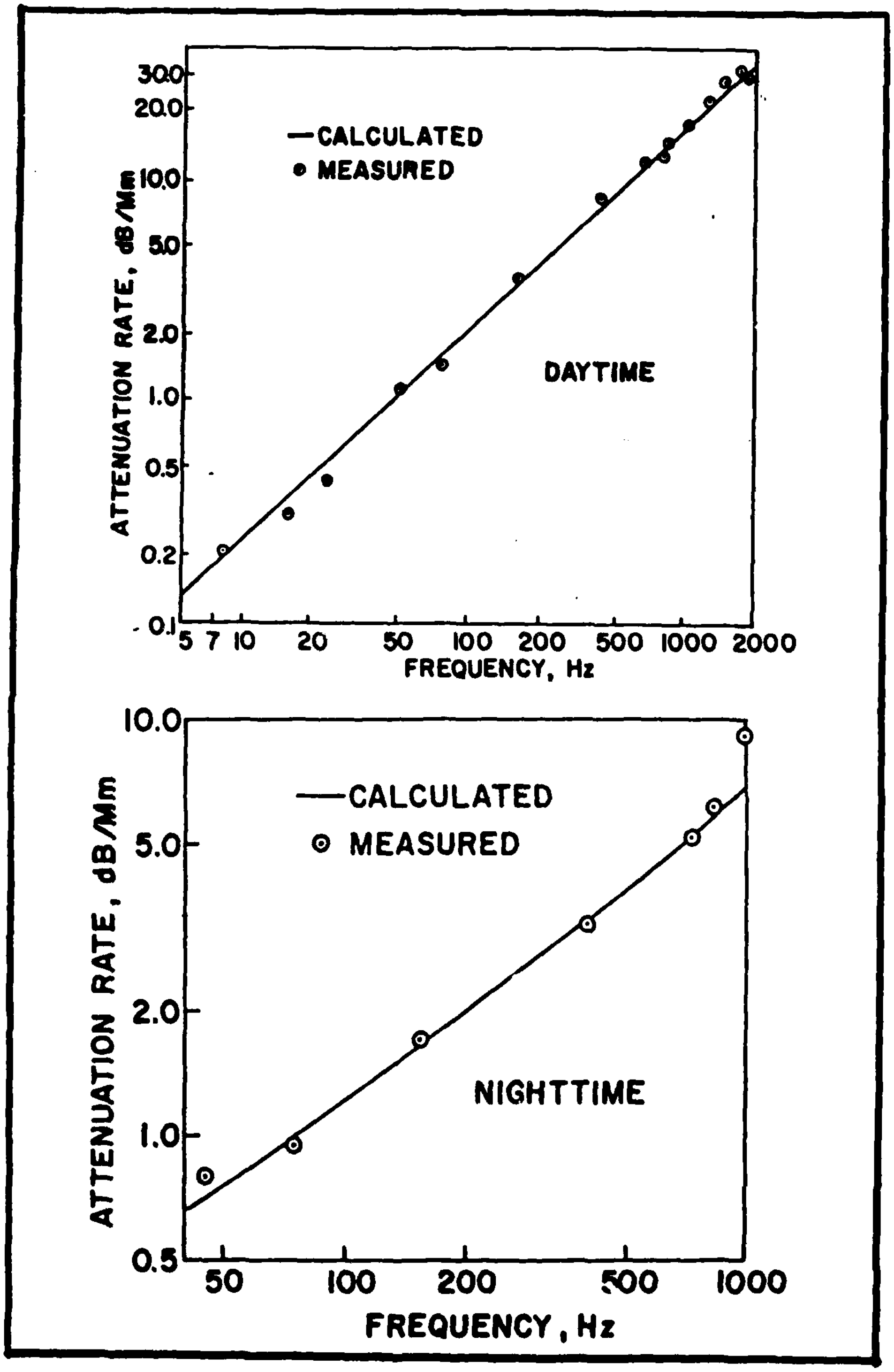

Figure 4.3 - Day and night Earth-ionosphere waveguide attenuation rates [Ref. 27: p. 10-27].

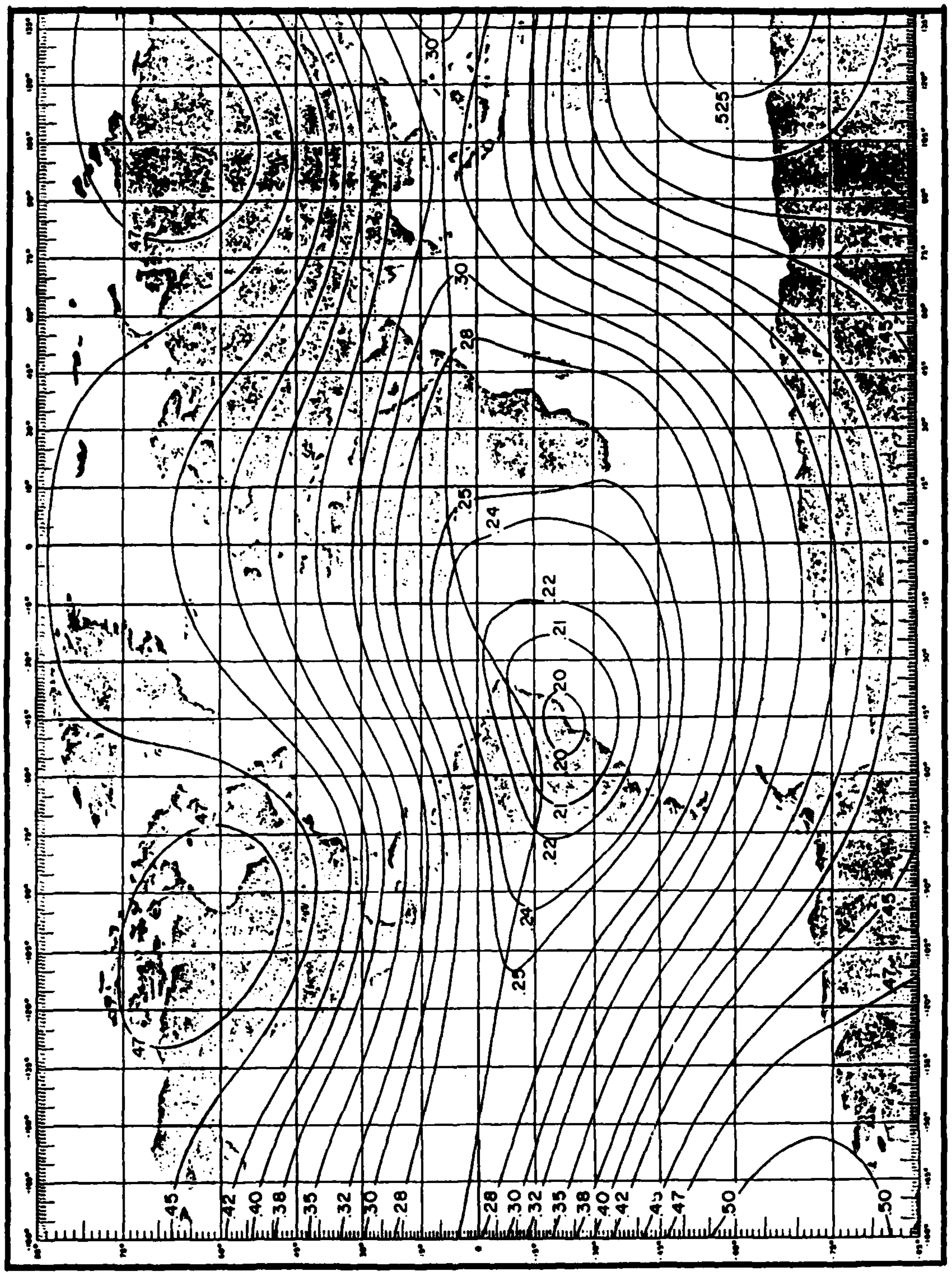

Figure 4.4 - Lines of constant B (Gauss) at 500km altitude [Ref. 28].

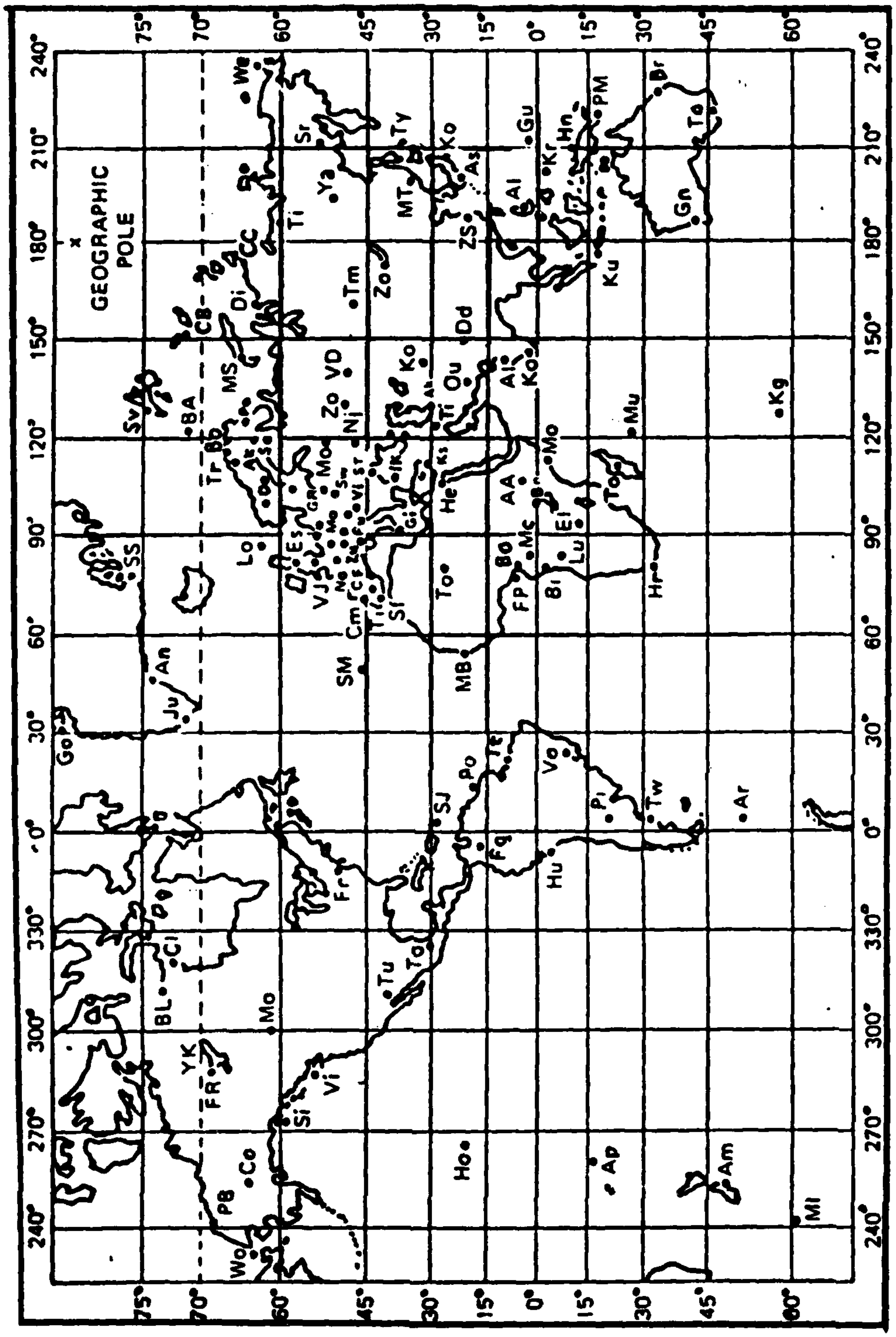

Figure 4.5 - The world in geomagnetic coordinates [Ref. 29].

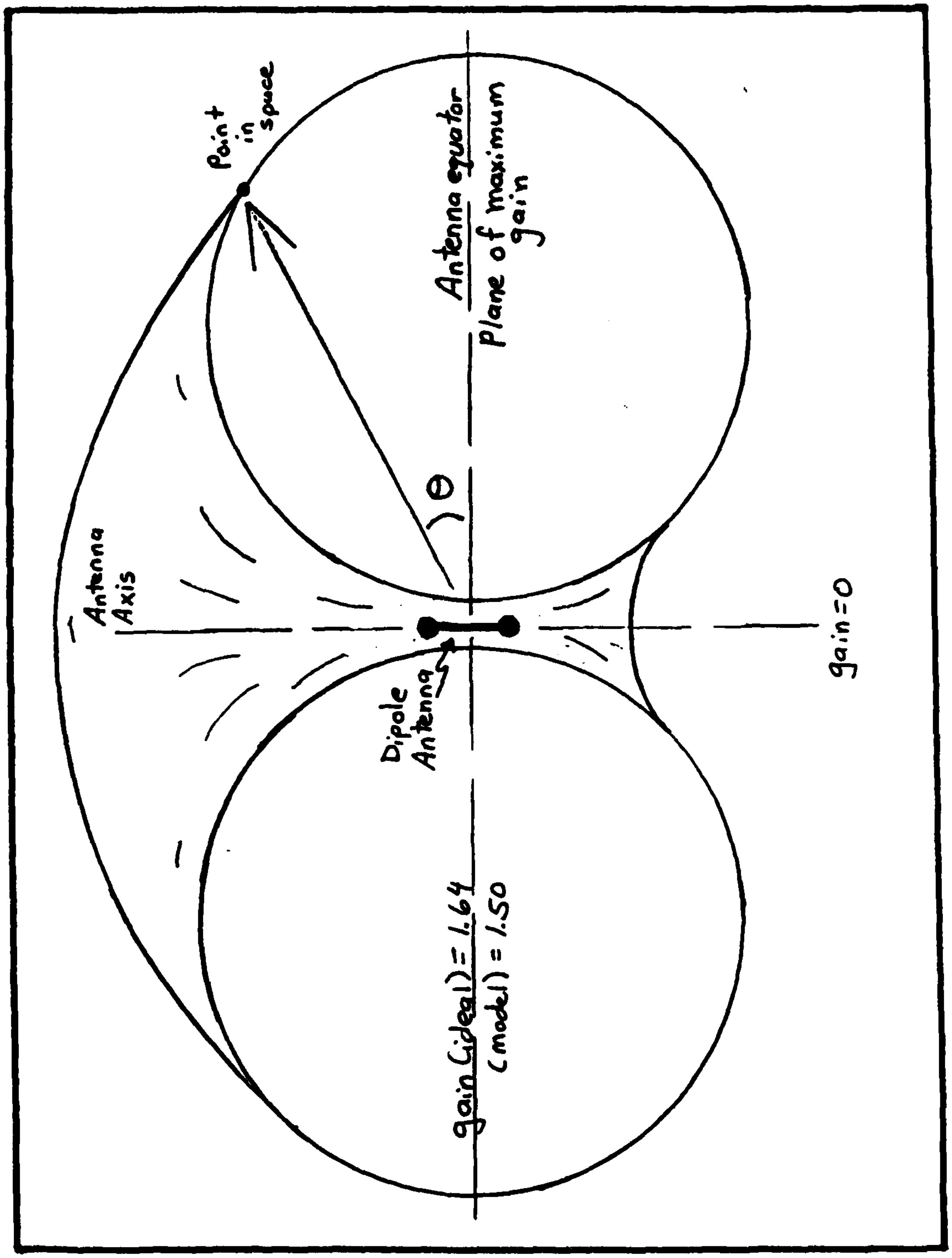

Figure 4.6 - A dipole antenna radiation pattern.

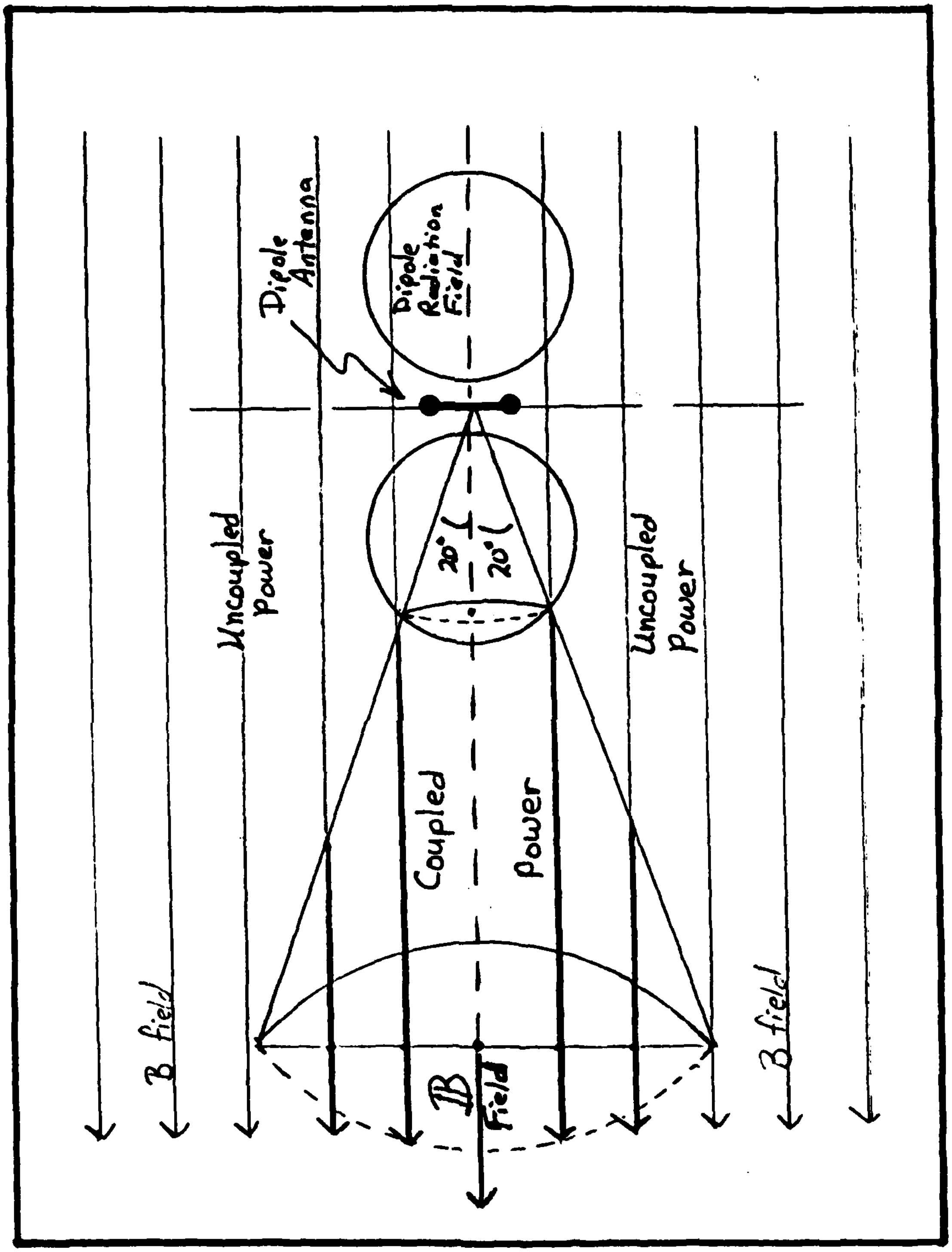

Figure 4.7 - Maximum available power coupling configuration.

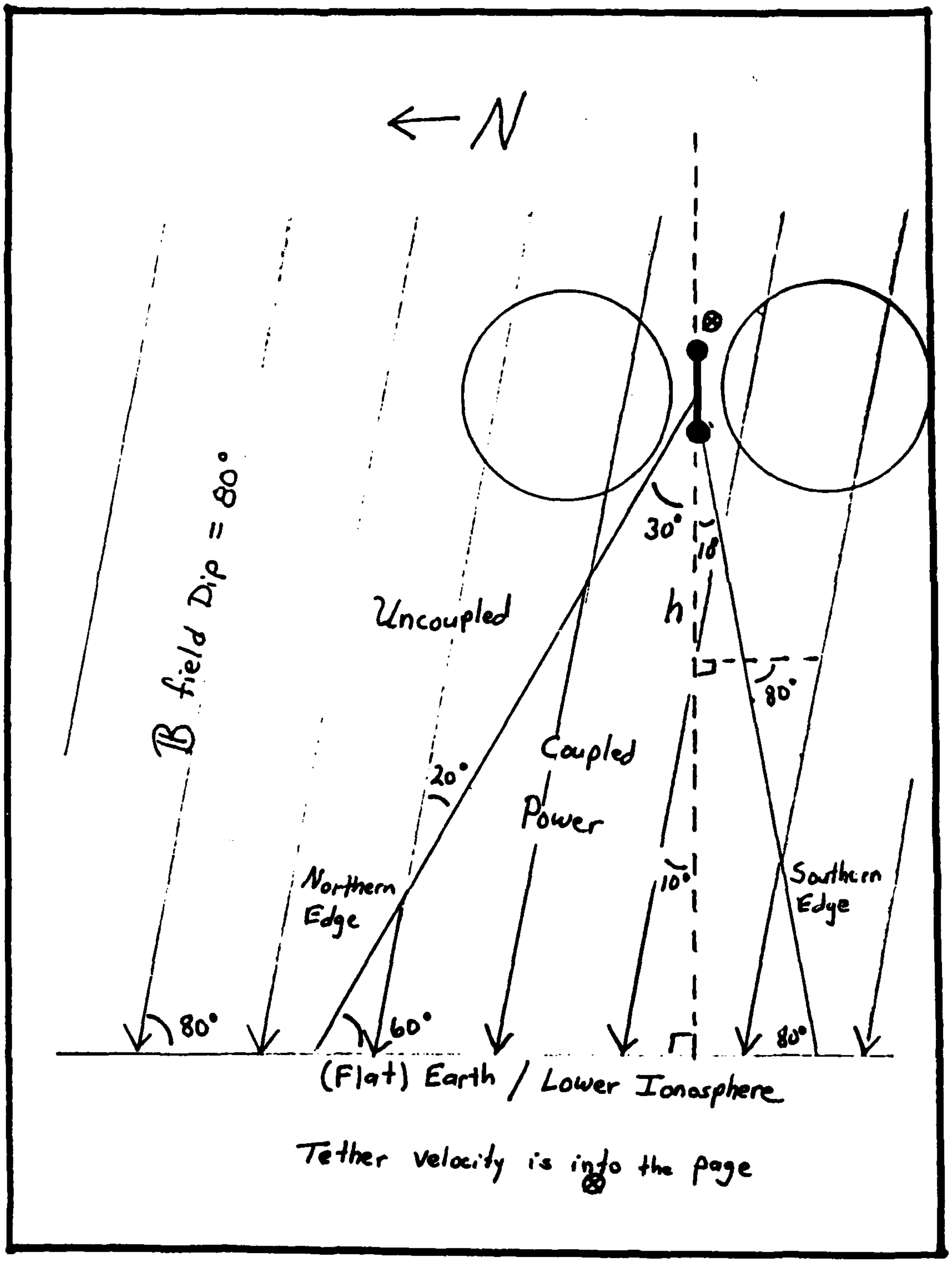

Figure 4.8 - North-south crosscut of radiation pattern, looking east.

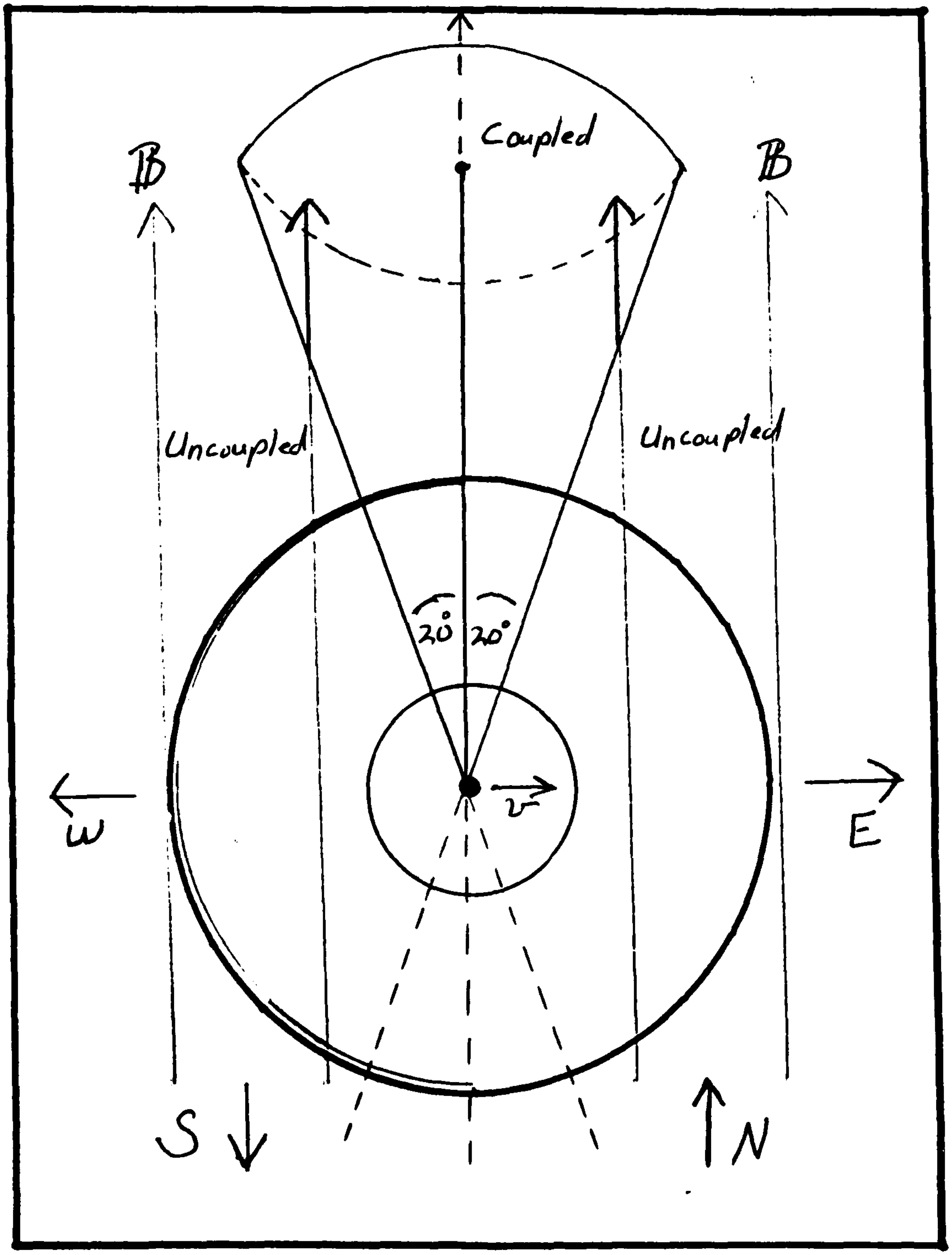

Figure 4.9 - Radiation coupling pattern as viewed from above the antenna, looking down.

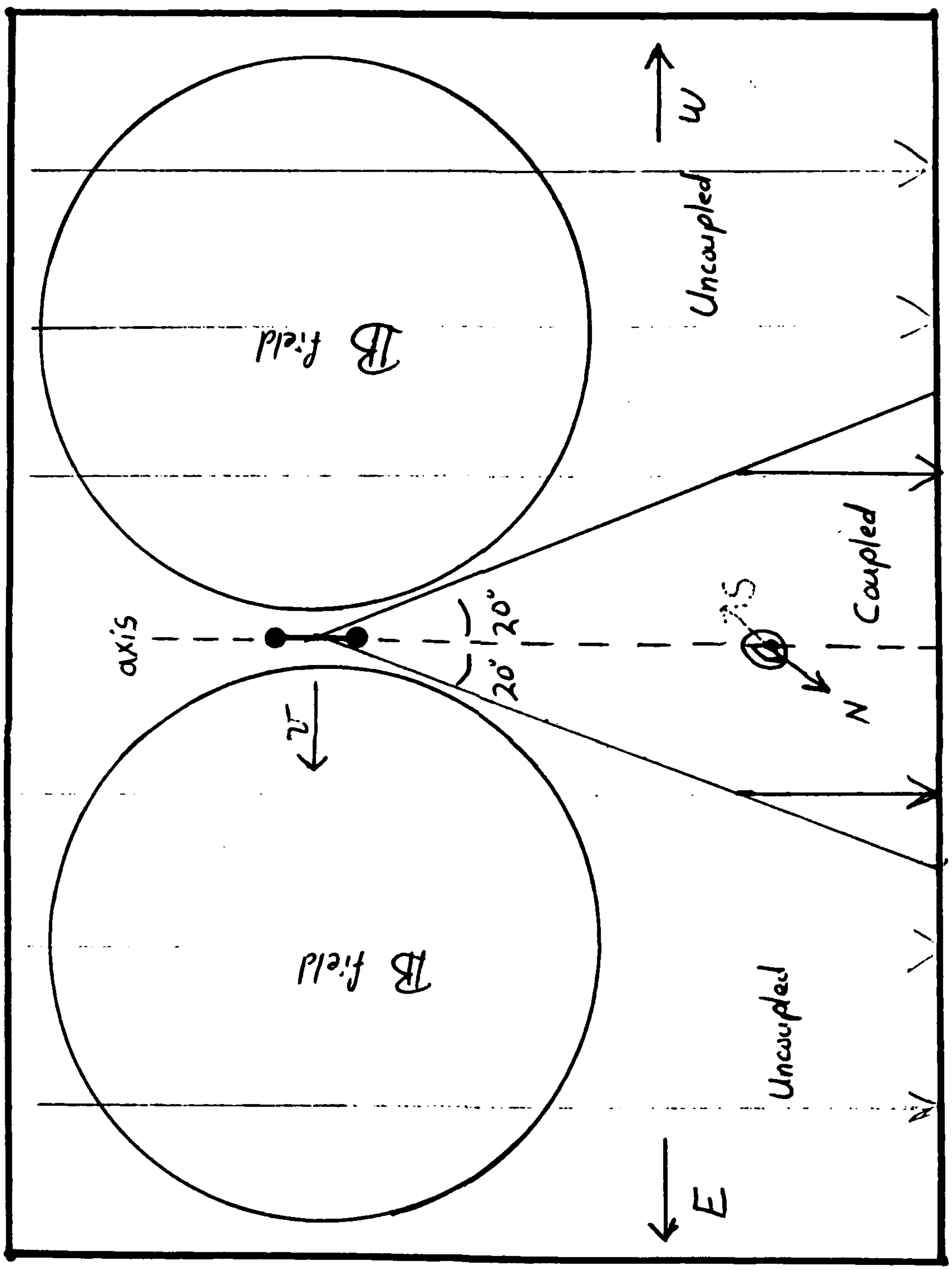

Figure 4.10 - East-west crosscut of radiation pattern, looking south.

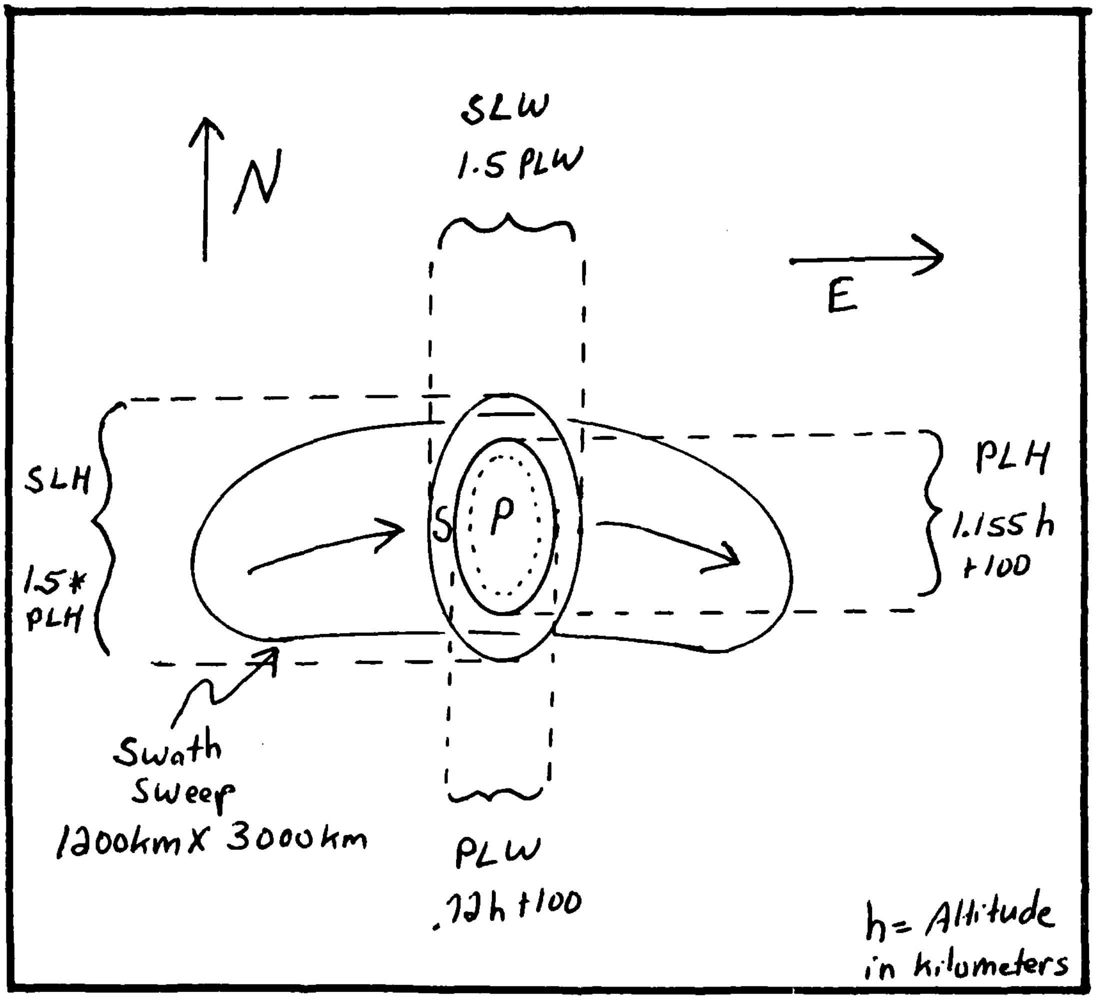

Figure 4.11 - Primary and secondary footprints with the sweep coverage area.

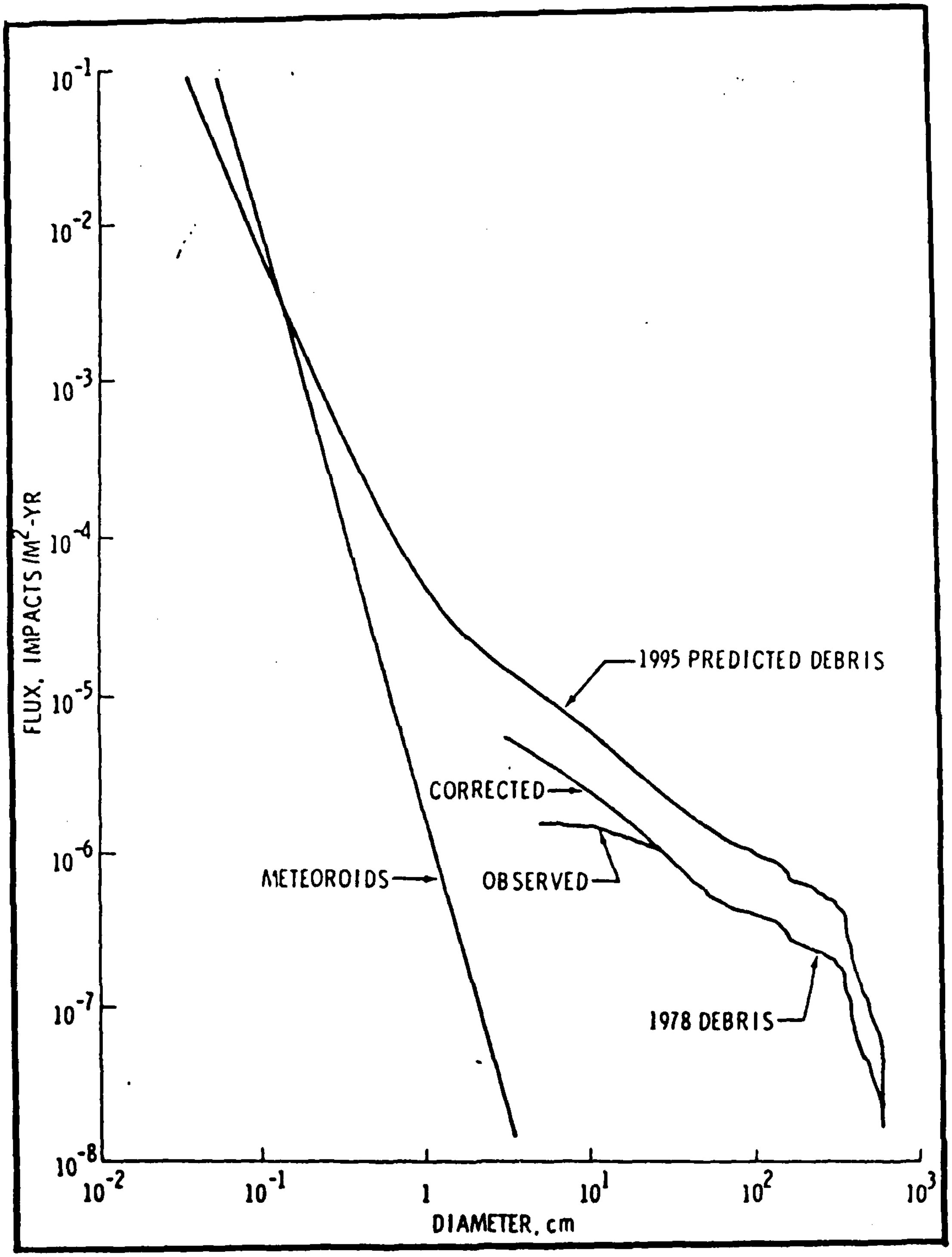

Figure 5.1 - Projected space debris flux for 1995 [Ref. 31: p. 359].

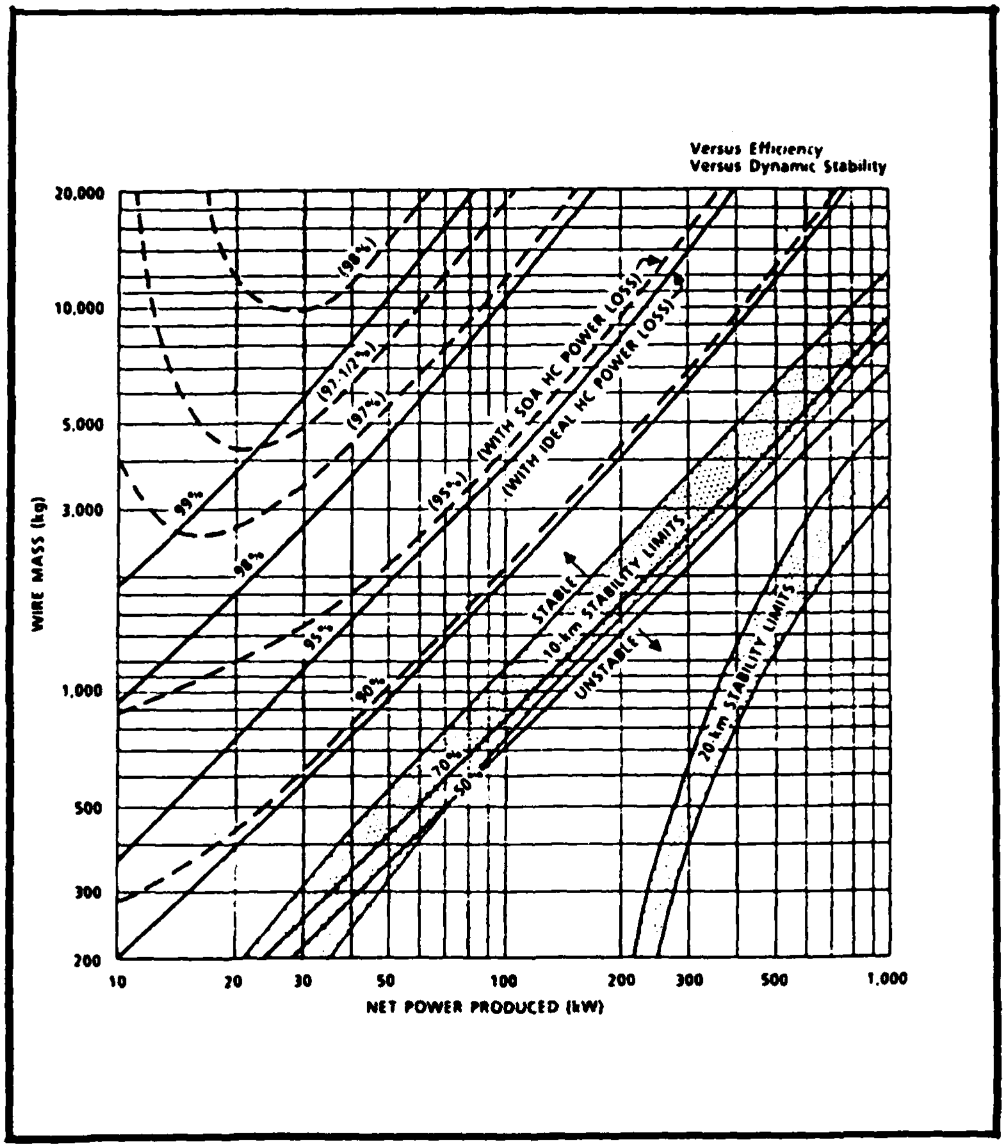

Figure 5.2 - Tether wire mass vs. net power produced [Ref. 23].

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